ASEE 2022 ANNUAL CONFERENCE
Excellence Through Diversity
MINNEAPOLIS, MINNESOTA, JUNE 26TH-29TH, 2022 ASEE

Paper ID #36884

Opening Up the Black Box: an Augmented Reality Look into the Scanning Electron Microscope

Megan Ngo

Ms. Ngo is pursuing her bachelors in Mechanical Engineering at MIT with a minor in Computer Science. She worked at LEAP Group under Dr. John Liu and Emily Welsh from 2020 to 2021, developing augmented reality experiences for nanotechnology education. Her interests include innovating education technology, as well as exploring new applications of computer vision. She hopes to merge her background in mechanical engineering with computer science to create new modes of digital experiences.

Emily Welsh

Ms. Welsh works as an educational technologist in the LEAP Group at MIT. Her work includes the development and running of MOOCs, the development of digital education tools, and researching how digital tools impact learning. Her background is in mechanical engineering with a focus on manufacturing. Prior to joining MIT, she worked at an original equipment manufacturer.

Kachina Studer

Benita Comeau

Nicholas Xuanlai Fang

John Liu (Dr.)

Dr. John Liu is the principal investigator of the MIT Learning Engineering and Practice (LEAP) Group, which applies design and systems principles to solving challenges in learning and develops learning experiences to better meet the increasing demand for STEM skills in tomorrow's workforce. He is a Lecturer in MIT's Mechanical Engineering department and Scientist of the MITx Digital Learning Laboratory. Dr. Liu's work includes engineering education, mixed reality and haptic experiences, workforce solutions to address the nation-wide manufacturing skills gap, open-ended assessments for scalable education settings, and instructional design theory for massively open online courses.

Opening Up the Black Box: an Augmented Reality Look into the Scanning Electron Microscope

Abstract

The scanning electron microscope (SEM) can serve as a gateway for introducing students to the nanoscale world. Traditional instruction for the SEM may be broken into two parts: concept-based instruction on how an electron interacts with various materials, and skills-based instruction on the operation of the SEM. A disconnect can arise between fundamental atomic-level concepts and hands-on lab skills as students may have a tendency to treat the SEM as a "black box". This tendency comes from the enclosed nature of the SEM that renders its inner workings inaccessible to visual inspection and tactile exploration. By addressing these instructional gaps, we aim to promote mastery of SEM imaging techniques through a more complete understanding of SEM operation and electron beam theory. Augmented Reality (AR) is a promising medium to help students visualize these concepts because of its ability to display and manipulate virtual objects in a realistic context.

We present the pedagogy, design and development, and initial course implementation of a vision-based AR app to teach the architecture and working principles of the SEM. The app enables learners to "look into" the SEM and examine in 3D the different subassemblies of the SEM, visualize mechanical and electromagnetic phenomena within the SEM, and probe how these phenomena are affected by commonly-used imaging parameters such as working distance and magnification. This app has now been released into an undergraduate-level laboratory class ("Micro/Nano Engineering Laboratory") at the Massachusetts Institute of Technology (MIT). Students were assessed before and after the learning activity to measure cognitive and affective outcomes (N=5). The development of the assessment and analysis are reported. Results suggest that this visually-rich approach is motivating for students and can promote proficiency in SEM imaging.

1. Introduction

The emergence of nanotechnology, engineering structures on a near-atomic level, has pioneered some of the most groundbreaking technologies in medicine, material science, and computing. From creating longer lasting batteries to developing new treatments for vitiligo – the potential for application is endless. The United States, in particular, has capitalized on the market's profitability – establishing itself as a global leader in the field. In 2003, the U.S. passed the 21st Century Nanotechnology Research and Development Act – an effort to "authorize appropriations for nanoscience, nanoengineering, and nanotechnology research" [1]. According to a report from the National Nanotechnology Initiative or NNI, which coordinates federal nano research and development, the U.S. invested over $3 billion into companies and infrastructure after the act was passed [2]. In 2020, the nanotechnology market in the U.S. was estimated at US$16 Billion, accounting for a 29.53% share in the global market [3].

The sudden influx in funding sparked national innovation, but as the market grows in influence, so does the demand for the necessary academic infrastructure to support the newest wave of nano engineers and researchers. Roco described the importance of education for the future development of this field: “One of the ‘grand challenges’ for nanotechnology is education, which is looming as a bottleneck for the development of the field” [6]. Reinforcing a better understanding of nanoscale is important if one strives to understand how matter is constructed and how the properties of materials reflect their components, their atomic composition, their shapes, and their sizes.

Imaging techniques such as scanning electron microscopy (SEM) are recognized as an important “gateway” tool for introductory students to view and understand material properties in the field of nanotechnology. The challenge, however, is the gap of knowledge between what is happening inside the electron microscope and the image produced. Because of the cost of equipment, visualization opportunities are limited by labtime and small student cohorts, and phenomena associated with imaging are often invisible (e.g. UV rays, electron beams). As a result, students have decreased opportunities to engage with the equipment, leading to a reliance on recipes or rules-of-thumbs, and a tendency to neglect the machine’s operations and physical principles. This limited engagement and lack of understanding towards working principles may inhibit students from gaining mastery over high quality imaging, accurate measurements, and being able to creatively and independently troubleshoot and extend techniques to new materials and sample types.

Challenges to growing a competent nano workforce lie within how we teach as well. In 2002, a group of scientists from Iowa State University understood the need for SEM exposure in K-12 education but saw a lack of initiative from SEM manufacturers to create a web-based, remote controllable application that did not require a skilled researcher to operate. As an early motivation, the paper states “[the SEM’s] capability to provide crisp, three-dimensional-looking images at high magnifications of objects from bugs to plants the SEM can bring the microscopic world to the K–12 student in a unique and exciting manner” [7]. However, given the high price of SEMs and the well-known shortage of funds available to elementary and secondary schools, it is understandable that companies see little chance for profit. Thus, the development of a SEM specifically designed for use in kindergarten-through-high school (K–12) classrooms is an area that has virtually been ignored. As a result, the research at Iowa State University made significant headway in the efforts of educators to create multi-modal experiences in the field of nanotechnology.

Evidence suggests true understanding and the ability to use knowledge in new situations requires learning in an authentic context that includes hands-on experiences [8]. Hands-on learning allows students to develop the ability to inquire themselves and become independent learners. COVID-19 further revealed the need for hybrid educational tools that mix in-person instruction with effective, remote instruction. In an early experiment, Copolo and Hounshell (1995) found that students in the group using both computer and physical models performed significantly better than the groups using either one of the models by itself [9]. Our motivation for an Augmented reality (AR)-based application aligns with this idea. Augmented reality technology attracts the attention of those wanting a remote learning experience with a connection to real-world interaction. As proposed by Azuma [9], AR can be defined as a system that fulfills three basic features: a combination of real and virtual worlds, real-time interaction, and accurate 3D registration of virtual and real objects. It exploits localization and object recognition technology to augment a user's digital experience with virtual objects in a context that is realistic. These augmented real objects create new visualizations that have potential to enhance students' understanding of abstract and invisible concepts or phenomena [10].

2. Design and Development

2.1 Design Goals

The first major goal for the SEM application was to understand the methodology of student learning in the given subject and lay out an experience which reflects the key explorations and takeaways. A major consideration was the application's ability to serve as a cohesive companion to the existing materials: to aid and elevate the learning experience. Positioned as a first of its kind augmented experience utilized in this capacity, it serves as a hybrid of simulation training and diagrammatic reasoning applications for object oriented familiarity and opportunity for hypostatic abstraction.

The typical structure for learning SEM image capturing begins with a lecture about imaging history and development, followed by a live demonstration where students learn how to prepare samples and make adjustments to produce a clear image. The adjustments have different names depending on the instrument maker, and it is not always obvious what the adjustments are doing physically. One simply "sees" the sample more or less clearly, perhaps without understanding how each adjustment works. Our goal for the app is to shift the student experience from studying the SEM through 2D diagrams (Figure 1a) to interacting with a digitally augmented rendering (Figure 1b), thus allowing students to visualize components within the machine in a realistic context.

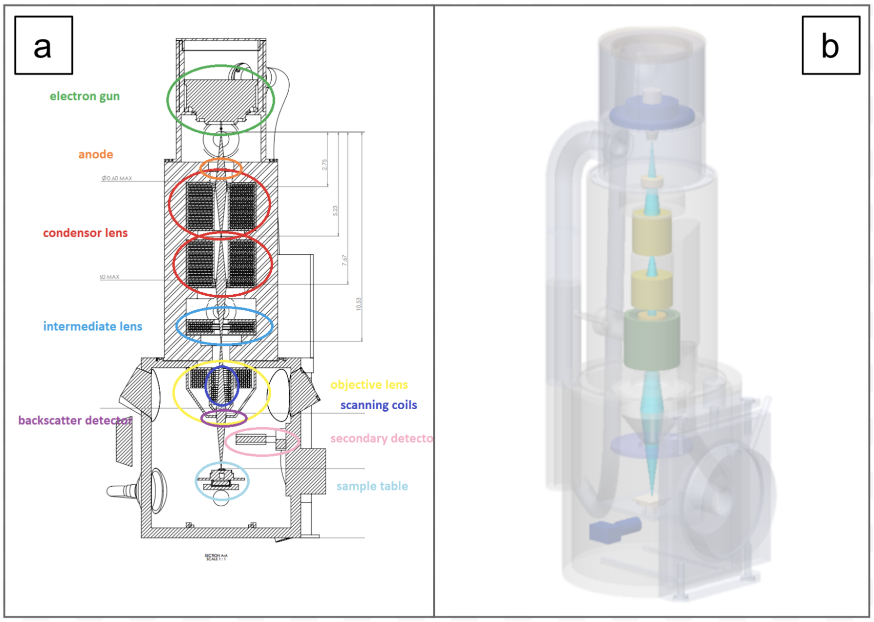

Figure 1. Comparing two methods to display the inner components of the SEM, a) a 2D traditional cross section and b) a 3D rendering with the outer casing transparent. The 3D rendering allows for a deeper spatial understanding compared to 2-dimensional diagrams.

Users are given a unique physical image, similar to a QR code, to serve as the image target (or anchor) which the AR engine recognizes to place virtual objects in the correct context. By calculating the real-time position and orientation of the image target, the engine superimposes a virtual 3D model of the SEM onto the image target on the screen.

The learning restrictions imposed by COVID-19 led to a spike in demand for effective approaches to remote learning. In our efforts to address this, we emphasized adaptability and flexibility in our design. The application is intended for any mobile device, compatible with both Android and Apple users, making it suitable for a wide range of environments and flexible working hours.

2.2 User Interface Design

The application offers two functionalities – Transparency and Labels – as well as two major "modes" of exploration for the user – Electron Beam Manipulation, and Stage Manipulation (Figure 2). The help icon in the top left provides a guide to the User Interface (UI). Although students have the freedom to navigate each mode in whichever order they choose, the initial tutorial guides them to explore the Transparency and Label functionalities first. Playing with transparency ensures that the student is aware of the capability to see the inner workings of the machine, while toggling the labels allows the student to associate these new components with additional background information.

Figure 2. A flow of the UI: a) the machine introduction where users are able to toggle b) labels and c) transparency on/off throughout the activity. Additional capabilities include manipulating d) the electron beam, and e) the stage to see changes to the quality and position of the resulting image.

Human factor consideration led to a hybrid interface structure, incorporating elements of three-dimensional spatial interface and two-dimensional screen overlay to achieve a higher quality of user experience and improve learning outcomes. Alpha testing performed by the internal development team concluded that user interfaces skewing heavily towards two-dimensionality or three-dimensionality were cumbersome for users and did not provide the desired outcomes for the interactive experience. User engagement was broken down into modules with the ability to explore learning concepts in separate experience panels (sections). Each of these panels was provided through a menu option which was kept minimal on the users screen creating adequate transparency for the augmented reality experience to be viewed. Information and in application support was provided for user onboarding and in app navigation to reduce the friction of new users or returning users needing quick support. Building consistency of user interactions between panels and viewing modes improved familiarity for students' exploration. Through iterative testing, button placement and size were altered to accommodate for the user's mobility while they explore the app. Sliders and buttons are within reach of either side of the screen, and major visual pop ups can adapt to fit larger dimension screens.

2.3 App Modes

When students first open the application, a homepage immediately provides instructions and a requirement for the user to possess a QR Code, given to students by the course instructor. guiding the user through the user interface (UI).

The user is able to toggle on/off the transparency of the outer casing of the SEM, as well as labels that point to key components of the machine. Each label also serves as a button to a pop up description window where the user can read more about the component (Figure 3). Seeing the SEM in a real-world context, students relate machine components that they have seen on paper to physical objects in 3D-space.

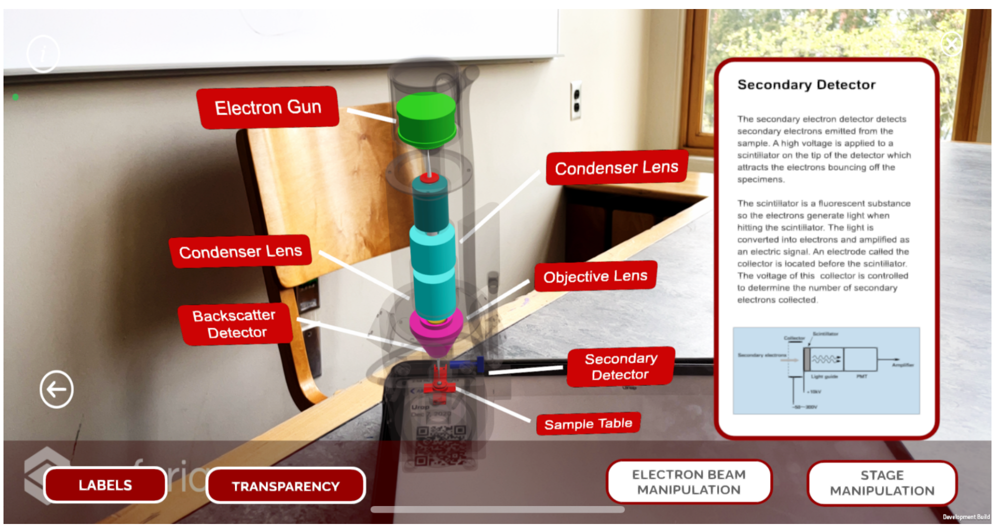

Figure 3. Labels and Transparency are toggled ON. When transparency is ON, the outer casing of the SEM becomes transparent and the inner components highlighted. The user is able to click on any label and see a description of the component as well as useful figures that may aid in understanding.

During the design of this application it was important to focus on concept accuracy rather than exact representation. Students are often bombarded with content to a point where feeling overwhelmed might prevent them from observing the effects of AR in virtual learning. Instead of including every adjustable parameter, we narrowed the initial design to include three well-known parameters: magnification, working distance, and beam intensity.

The components of the SEM are rendered transparent in order to visualize the shape in which the electrons travel during imaging (Figure 2d). Parameters such as magnification, beam intensity and working distance are controlled by sliders that manipulate the shape of the electron beam and the spot size (visualized in top right of Figure 2d, Figure 2e). The beam and the stage affect the image differently. While a student might assume image focus is only affected by working distance, an important concept to note was how changing tilt and z-direction (not pictured) affected the spot size which also affected the focus of the image. This concept was especially important for the instructor, due to the amount of times in the lab where students would have trouble focusing their image. In the traditional lab, students change stage tilt and translation, beam intensity and magnification in any order and as many times as needed to capture a clear image. Similarly, the AR app was designed to allow the student to jump back and forth between Electron Beam Manipulation and Stage Manipulation as well as manipulate several parameters at once. The augmented image allows students to project the simulated SEM on top of or next to the physical SEM. This facilitates an intuitive understanding of the scale of the electron beam and movement of the stage better than a non-augmented experience could provide.

2.4 Application Development

The Unity engine, a platform for 3D app and game development, was used to develop the application because of easy deployment to both Android and iOS devices. We used the Vuforia AR engine, an augmented reality software development kit (SDK) for mobile devices with Unity compatibility. Unity's multi-platform build capabilities allowed for very seamless testing and quick release of initial design concepts. Simple user interface (drag and drop functionality) removed the barrier for design when it came to creating buttons and sliders for each mode. Unity also provided independence for designers to create custom button and slider functions using C++ that allowed for the user to manipulate the parameters independently and simultaneously.

When it came to integration with Vuforia's AR engine we ran into several limitations for the manipulation of 3D objects in space. Specifically, the positions and poses were defined by a moving origin rather than a stationary frame, leading to challenges in object manipulations and scaling. As a result, a line-renderer object was used to create the electron beam shape enabling scaling a single parameter using a simple linear slider. For initial release, the application was given to students using Testflight, a beta-testing platform for iOS devices using Apple ID.

3. Methodology

3.1 Student Testing

We piloted these activities in the Spring 2021 course of "Micro/Nano Engineering Laboratory," a course in the department of Mechanical Engineering at MIT. The goal of this laboratory intensive course is to give mechanical engineering students an introduction to engineering at small length scales through direct experience of micro/nano scale phenomena. Students attend three hours of lab instruction each week, where they build, observe, and design experiments in micro-electromechanical systems, microfluidics, and nanomaterials. They rely on advanced imaging systems such as SEM, atomic force microscopy (AFM), scanning tunneling microscopy (STM), and inverted fluorescent microscopy in order to observe and manipulate these small scale objects. The course is typically taken by junior and senior undergraduate mechanical engineering students as their introduction to micro-nano topics and as their first exposure to advanced imaging systems like the SEM.

Ten students were enrolled in the course and given the intervention. A cohort of five students completed a pre-assessment, used the AR-enhanced SEM activity, performed the traditional lab sequence, and completed a post-assessment. Five additional students performed the traditional lab sequence, used the AR-enhanced SEM activity, and completed the post-assessment without a pre-assessment. Due to this difference in usage, we will consider two data sets: the pre- and post-assessment results of the cohort of five students, and feedback on the AR activity from all 10 students.

The learning objectives of the AR SEM activity were that by the end of the lab, students can:

- Identify different SEM sub-assemblies and explain their functions.
- Explain the relationship between coil current, beam shape, beam intensity, working distance, and spot size.
- Define image magnification.
- Explain the relationship between stage travel, tilt, image translation, and spot size.

The first section of the pre-assessment activity consisted of 19 questions on a 7-point Likert scale (1- “not at all true of me” to 7 – “very true of me”) adapted from the Motivated Strategies for Learning Questionnaire (MSLQ) [11]. Ten questions were written to measure three types of self-efficacy: an individual’s belief in one’s capacity to learn the content (3 questions), to apply the necessary skills to equipment (3 questions), and to perform well in the class (4 questions). Five questions measured motivation to re-engage with the content and four questions measured their fear of making mistakes. Each theme was covered by multiple Likert scale questions to measure the average over multiple questions to normalize for variation in question phrasing and learner response and decrease measurement error. In the second section of the pre-assessment activity, the students were asked eight questions on technical aspects of the SEM including correctly identifying components, understanding what components do, identifying causes of poor imaging, and how the SEM reacts to user inputs. These technical questions were intended to measure the students cognitive outcomes.

The post-assessment activity repeated the 19 Likert scale questions from the pre-assessment activity then asked students eight technical questions on the SEM of similar quality to the pre-assessment technical questions. The post-assessment activity also added a third section with three 7-point Likert scale questions:

- *I liked learning using AR.*
- *I learned useful knowledge about the SEM using AR.*
- *I would prefer to learn about the SEM using AR as opposed to traditional text and graphics.*

Two open response questions asked how the AR facilitated or distracted from their learning and if they had any additional comments.

3.2 Data Analysis

To analyze the pre- and post-assessments, the Likert scores were grouped by category and averaged across the five student responses. A paired t-test was performed to compare the pre- and post-assessment values. The hypothesized mean difference (HMD) was then calculated based on the t-test, means, and standard deviation. The cognitive questions for pre- and post-assessments were graded for each learner. Blank questions were considered to be incorrect. The total score for each student was found and the average, standard deviation, paired t-test and HMD were calculated. The results of this analysis are given in Table 1. The pre- and post-assessments are given in the appendix.

The ten responses to the Likert scale questions in the third section of the post-assessment were averaged across the students. Averages and standard deviations are given in Table 2.

4. Results

Based on an alpha for confidence value is 0.05 there are no statistically significant differences between the pre- and post-assessment self-efficacy and fear scores. This may be due to the small sample size. The increase in student motivation to re-engage with the content is statistically significant.

Table 1. Pre- and Post-Assessment Affective Data (N=5).

	Pre		Post		Paired t-test P-Value	Confidence Value	HMD
	Average	Sample σ	Average	Sample σ			
Self-efficacy - Learning: (Questions 2, 8, 9)	5.07	0.88	4.87	0.83	0.19	81.13%	-0.26

Self-efficacy - Application: (Questions 1, 4, 11)	4.93	0.96	5.07	0.80	0.63	36.63%	-0.07
Self-efficacy - Performance: (Questions 7, 13, 17, 18)	5.85	0.81	5.75	0.91	0.54	45.91%	-0.27
Motivation to Re-engage: (Questions 5, 10, 12, 15, 19)	3.92	1.53	4.32	1.57	0.05	95.25%	0.37
Fear of Making Mistakes: (Questions 3, 6, 14, 16)	2.15	0.98	2.45	1.57	0.25	75.08%	0.18
Cognitive Assessment Score	6.00	1.00	4.80	0.84	0.07	92.95%	-1.24

Students had a greater than average opinion of the AR experience on the Likert scale (Table 2), however student enjoyment was highly variable. As a whole, students rated their experiences as above average on the Likert scale. Comments such as "It gave an easy to understand 3D visualization of all the parts of the SEM machine, with nice breakdowns for most of the components. I thought it was very helpful." reflect this overall enjoyment. Learner feedback reflects some mixed reactions to the AR activity itself with comments such as "It was an effective way to learn about and visualize the parts of an SEM (I liked the part with the sliders that let you change the beam intensity, working distance, magnification, etc.). But I personally didn't think the AR aspect itself was helpful." and "It was interesting to be able to see inside of the SEM. I think it helped me learn the parts and really see some of the effects of changing one element (e.g. beam intensity, tilt, etc)."

Table 2 Post-Assessment AR Likert Questions (N=10).

	AB		BA	
	Average	St. Dev.	Average	St. Dev
AR Enjoyment	4.6	1.67	5	2.12
AR Learning	5	1.58	5.2	1.10
AR vs. Traditional Preference (7 is preference for AR)	4.2	1.30	5.4	1.52

5. Conclusion and Future Work

We created an AR app to open up the "black box" of the SEM and allow students to investigate the different components and functions of the machine. The app was piloted to a small group of students in Spring of 2021. Students were given pre- and post- assessments to measure changes in their self-efficacy, willingness to re-engage with the content, and fear of making mistakes as well as their conceptual understanding of the SEM. We found that students who used the AR app did exhibit a statistically significant increase in willingness to re-engage with the SEM after the course. Learner feedback indicates that the app was able to reduce the black box aspect of the SEM, but additional app development is necessary to improve learner immersion and deepen the learning experience.

Implementing this instruction also led to improvements in learner engagement, flexibility, and access. Because only one student can use a SEM at a time and instructional labs typically only have one SEM, those who are not using the SEM experience “downtime” and can become disengaged. Our presented work gives every student access to an interactive and hands-on activity to learn about the SEM, alleviating the bottleneck in instruction and maximizing the value of student time in the lab. Also, because this interactive activity is virtual and not chained to the laboratory, it is both COVID-resilient and can be flexibly implemented – instructors have the option to assign it in different settings outside the lab such as lecture, or as a pre-lab or post-lab activity. Finally, because the app is free and only requires a smart device and a printout to use, it can be made available to high schools, colleges, and resource-constrained education settings. The app shows strong potential in improving micro-nano SEM instruction by increasing students' understanding of the inner workings of the SEM, and making the SEM accessible to more than one learner, in more than one environment.

Further improvements will include refinements to the tilt and stage movement areas of the app including tilt stacks of a scan so that the image accurately changes angle and focus with tilt, an updated UI to address the issues students gave feedback on, and updated component labels to include information on the anode, intermediate lens, and scanning coils. Additional visualizations of the electron beam such as the coil glowing based on the current passing through them and visualizations of the magnetic lenses created by the coils will improve the students' spatial understanding of the electron beam. A function to connect the AR app to the SEM for real-time viewing of changes within the SEM would allow all students to see changes in the electron beam and stage position. Establishing a real-time connection would further reduce the “black box” nature of the SEM and alleviate the bottleneck due to limited machine availability. And as efforts have already been made to efficiently allow educators and students to operate the SEM in real-time from a remote location using multiple-client PC’s over the internet [12], a real-time connection to the AR app would offer these remote learners improved opportunities for visualization and interaction. We also hope to conduct further research in collaboration with those who have primarily used the SEM remotely during their graduate or undergraduate careers. This would provide insight on the effects of a traditional remote learning experience as compared to one with augmented reality.

6. Acknowledgements

The authors thank Professor Jeehwan Kim and Professor Sangook Kim for their support in piloting these new learning methods in Micro/Nano Laboratory (2.674) and their feedback. Dr.

Glenda Stump gave helpful advice on self-efficacy assessment. Fatima Abbasi carried out hypothesis testing calculations. PTC Inc. provided Vuforia software and the PTC Education Programs team gave development support. This research was supported by the MIT Alumni Class Fund and the MIT Undergraduate Research Opportunity Program.

7. References

1. 21st Century Nanotechnology Research and Development Act, National Archives and Records Administration, 108th Congress Public Law, Dec 3, 2003, United States, U.S. Government Printing Office, 2003.
2. National Nanotechnology Initiative Supplement To The President's 2021 Budget, Nanoscale Science, Engineering, And Technology Subcommittee, Oct 2020.
3. ReportLinker, “Global Nanotechnology Industry,” *GlobeNewswire News Room*, 16-Jul-2020. [Online]. Available: https://www.globenewswire.com/news-release/2020/07/16/2062964/0/en/Global-Nanotechnology-Industry.html. [Accessed: 05-Feb-2022].
4. Dr M. Nachmani, “Plastic and nanoparticles - the perfect blend,” Hayadan, 04-Nov-2010. [Online]. Available: https://www.hayadan.org.il/plastics-and-nanoparticles-%E2%80%93-the-perfect-combination-0311104. [Accessed: 03-Feb-2022].
5. D. Johnson, “One-Nanometer Gate Dimensions for Transistors Have Been Achieved,” IEEE Spectrum, 07-Oct-2016. [Online]. Available: https://spectrum.ieee.org/onenanometer-gate-dimensions-for-transistors-have-been-achieved. [Accessed: 03-Feb-2022].
6. M. C. Roco, “Converging Science and Technology at the nanoscale: Opportunities for Education and training,” Nature biotechnology. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/14520410/. [Accessed: 03-Feb-2022].
7. L. S. Chumbley, G. Cassucio, D. Kritikos, H. Lentz, C. Mannes, and K. Mehta, “Development of a web-based SEM specifically for K-12 Education,” *Microscopy Research and Technique*, vol. 56, no. 6, pp. 454–461, 2002.
8. D. L. Haury, P. Rillero, Perspectives of Hands-On Science Teaching, Columbus, OH, ERIC Clearinghouse for Science, Mathematics, and Environmental Education, 1994.
9. H.-K. Wu, S. W.-Y. Lee, H.-Y. Chang, and J.-C. Liang, “Current status, opportunities and challenges of augmented reality in Education,” Computers & Education, vol. 62, pp. 41–49, 2013.
10. H. Tekedere and H. Göker, “Examining the Effectiveness of Augmented Reality Applications in Education: A Meta-Analysis,” International Journal of Environmental & Science Education. [Online]. Available: https://files.eric.ed.gov/fulltext/EJ1118774.pdf. [Accessed: 03-Feb-2022].

11. Pintrich, P.R., Smith, D.A.F., García, T., & McKeachie, W.J. (2015). Motivated Strategies for Learning Questionnaire (MSLQ) Manual. 10.13140/RG.2.1.2547.6968.
12. A. Yamada, “A practical method for the remote control of the scanning electron microscope,” *Journal of Electron Microscopy*, vol. 52, no. >2, pp. 101–109, 2003.