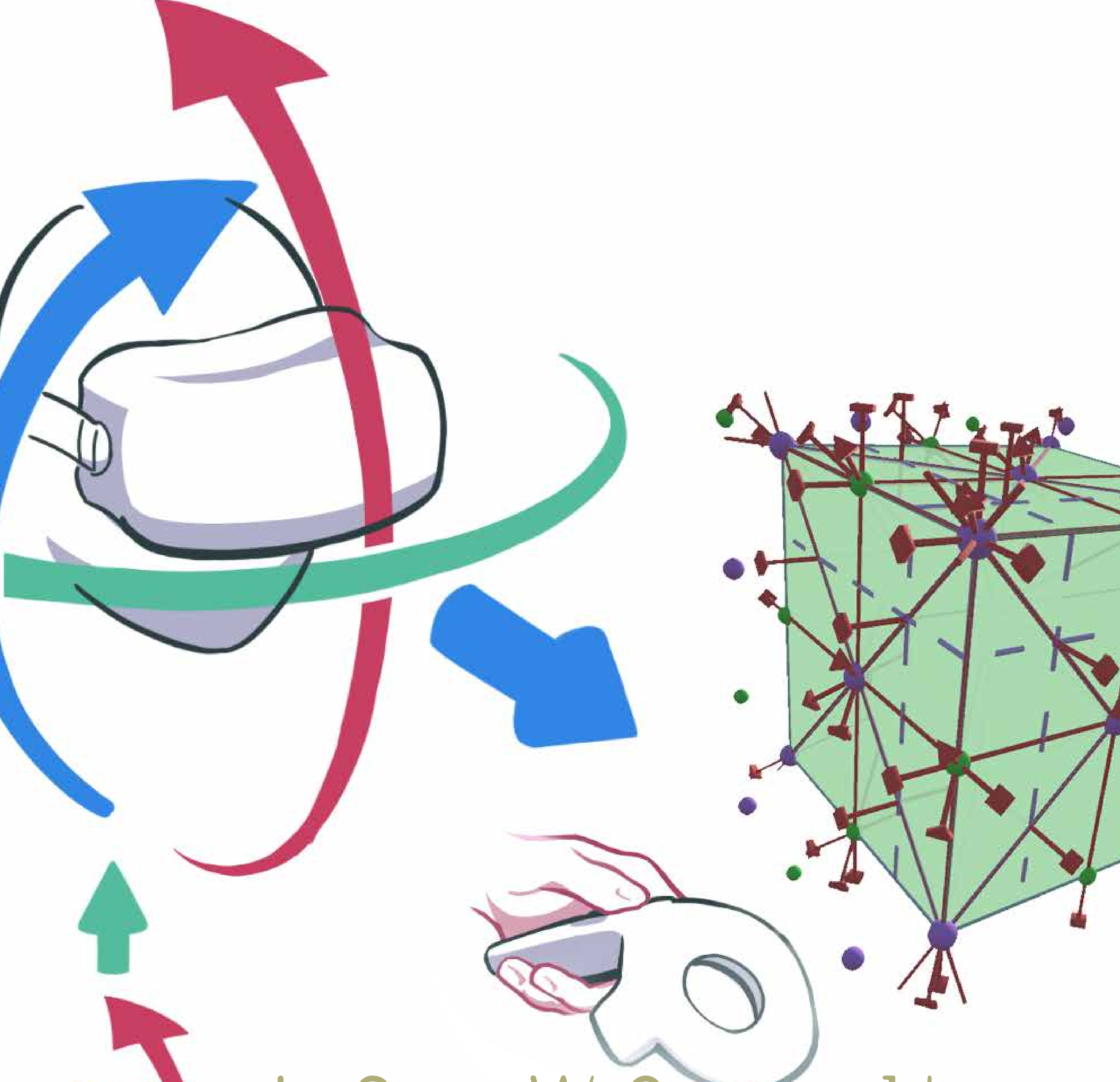

by Scott W. Greenwald
John Belcher
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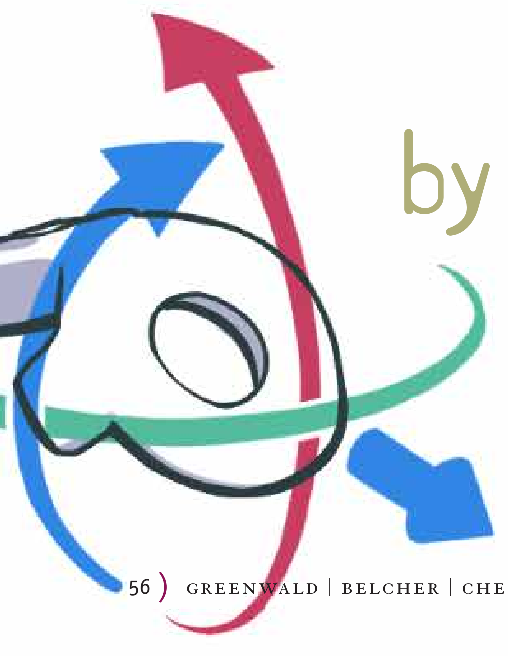
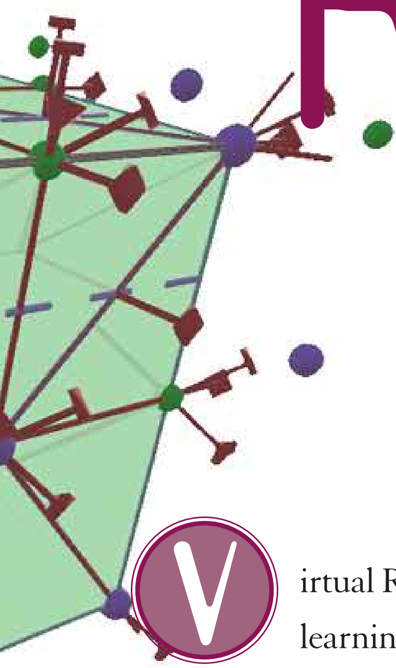


Virtual Reality in Physics Education and Research



Virtual Reality (VR) holds great promise as a technology for teaching, learning and discovery. Here at the MIT Department of Physics, we are investigating this potential in the context of physics research and education. Our approach is based on multi-user, simulation-based, exploratory learning, which we used to launch two projects. The first, ELECTROSTATIC PLAYGROUND, is designed as a supplement to freshman physics course, *8.02: Electromagnetism I*, and aimed at enhancing students' understanding of Gauss's law [1]. The second, CRYSTAL VR, explores crystalline structures for use in research, education and public outreach. Here, we provide an overview of these projects, chronicling lessons learned and resultant design principles. We conclude with a vision for the application of this technology at scale, along with a path forward leveraging the approaches presented here.

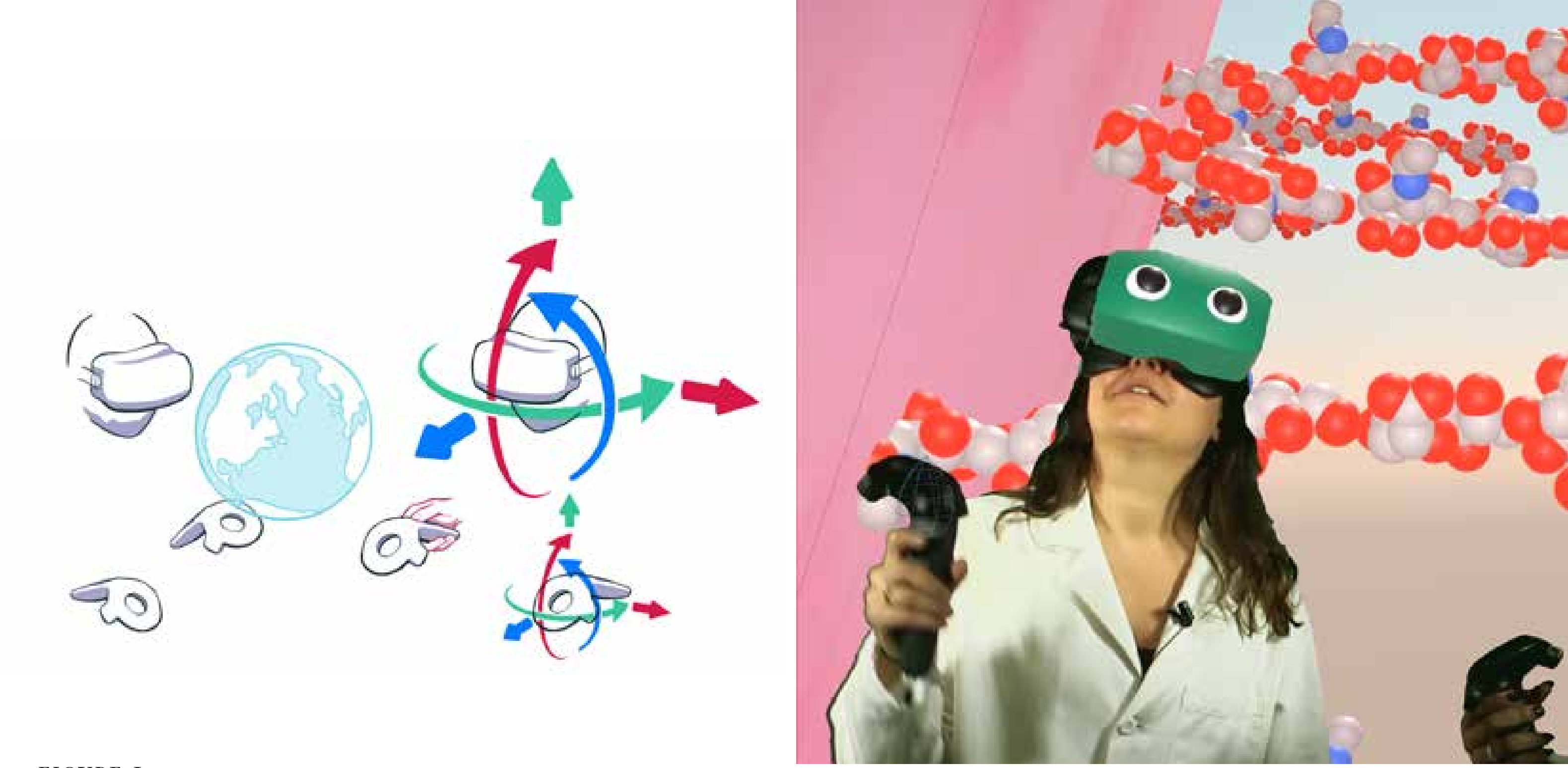


FIGURE 1

Six-degrees-of-freedom *(6DoF) tracking of the headset and handheld controllers creates an immersive world, which users move around and interact with naturally (left). Using the software we have developed, multiple users can share the physical and virtual space (right). [Credit: Body Quest Team, Greenwald, et al.]*

RECENT ADVANCES IN CONSUMER VR TECHNOLOGY have created the potential for new ways of learning that are especially applicable to physics. For readers unfamiliar with this technology, today's high-end consumer VR devices use a desktop computer similar in specifications to a gaming computer, including a high-end graphics card. The VR headset can be thought of as an additional display that is plugged into the same graphics card as the desktop display. Also, two wireless handheld controllers are provided for interacting with the virtual world [2].

Both the headset and the handheld controllers are tracked with six degrees-of-freedom (6DoF) —that is, both position and orientation are represented in the virtual world (*Figure 1*). Using this display technology, a user can simply move around a virtual object to view it from different angles, while it remains static with respect to the physical world. The handheld controllers occupy the same virtual space and can be used to reach out and manipulate such virtual objects directly. The objects can be placed anywhere, and their behavior and interaction with one another and with the users in the virtual space can be scripted by computer simulations appropriate to the physics. Further, it is not necessary to be bound to the human physical scale: a user can experience a virtual environment at any scale, and this scale can be changed dynamically.

Simulations in virtual reality

For specialists and non-specialists alike, visualizing physical phenomena is among the most challenging, albeit most rewarding, endeavors in learning and exploring physics. Simulation is a critically important tool in many fields of physics, as it allows this visualization to be externalized, thereby taking advantage of both computational power and sources of data that the mind cannot access directly. Interacting with simulations using a keyboard, mouse and 2-D display has certain limitations: viewing 3-D phenomena using a 2-D screen requires additional techniques such as interactive rotation or the viewing of slices of data in sequence. Specifying such

rotations or movements requires navigating a set of interface elements and mappings to physical input devices, which increases cognitive load (*Figure 2*).

VR promises to provide an improved interaction with simulation and data visualization in both of these areas, as a direct, stereoscopic 3-D view of 3-D phenomena takes greater advantage of the human visual system and requires less abstraction in the interpretation of data views. Further, using spatial input devices provides a more intuitive and efficient means to manipulate elements and parameters involved in simulations. This has been the motivation for building simulation- and data-oriented virtual reality environments for research and education in physics [3].

Exploratory learning and real-time collaboration

The use of VR and simulations expand the potential for exploratory learning and discovery. Learners can easily set up initial conditions that they are curious about and fill in gaps in their understanding by seeing what happens. Even seasoned researchers can quickly gain new insights through this novel method of inspecting and interacting with spatial representations and simulations.

Another advantage of VR is the ability to naturally and seamlessly collaborate in a virtual environment. Real-time collaboration on 2-D desktop computer displays has been a subject of extensive research in human-computer interaction, but the primacy of the single-user paradigm in both hardware (keyboard and mouse) and software (operating systems) sometimes makes collaboration in this environment challenging. By contrast, using VR technology can improve collaboration in physical reality. For example, remotely located researchers within VR can discuss the symmetry properties of a new quantum material with a model and its symmetries in hand.

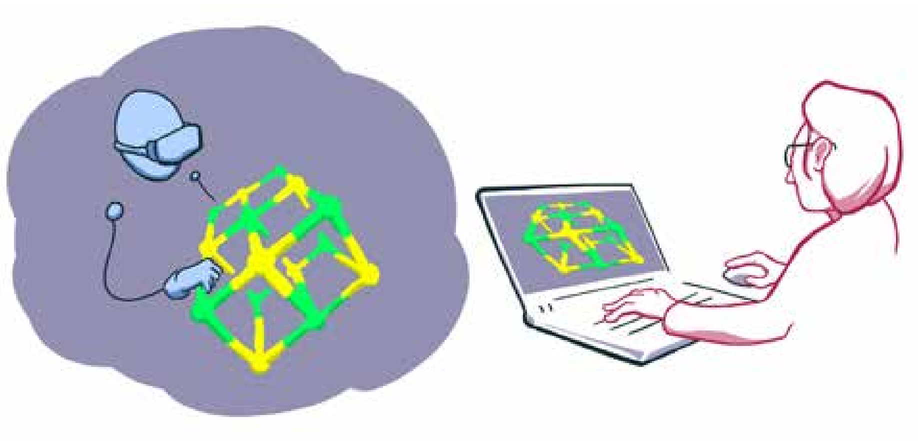


FIGURE 2

In VR, users can manipulate objects *and see new perspectives in a natural and intuitive way (left). Performing the same functions on a desktop computer using a keyboard and mouse requires a layer of abstraction (right). [Credit: Greenwald, Corning.]*

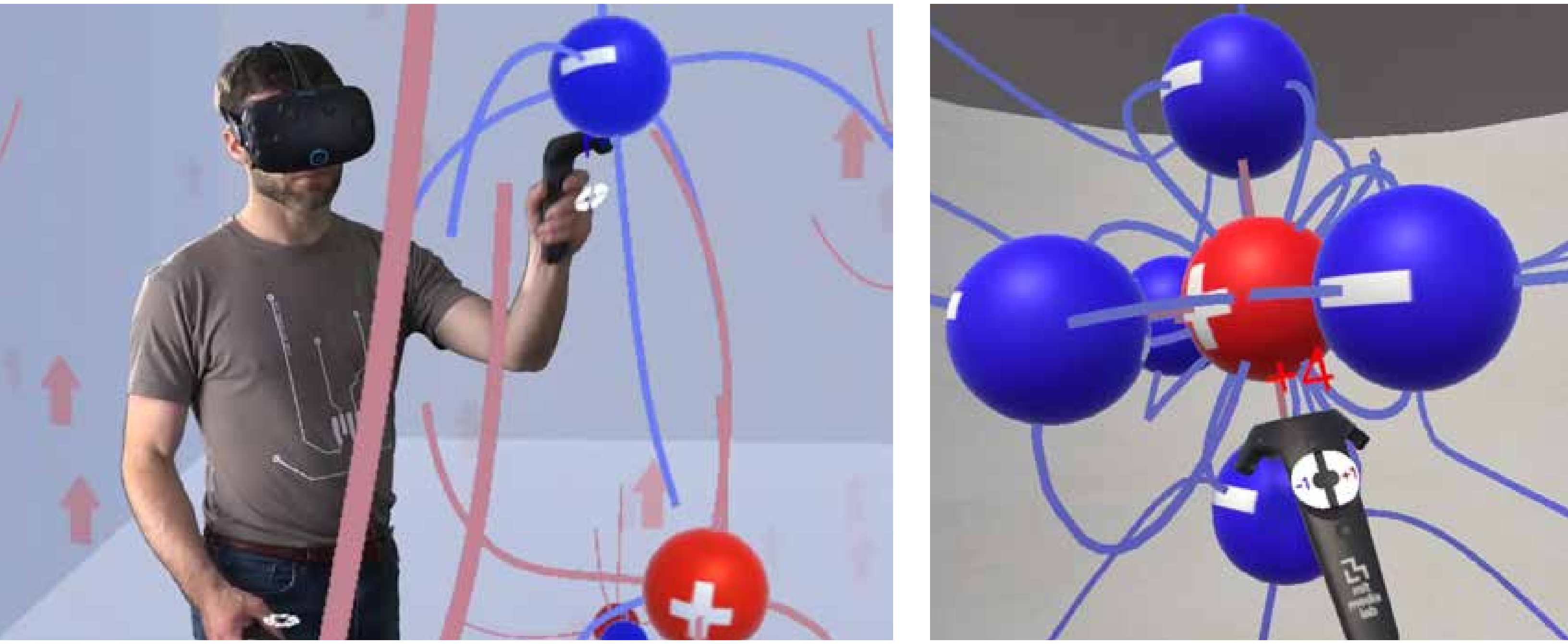


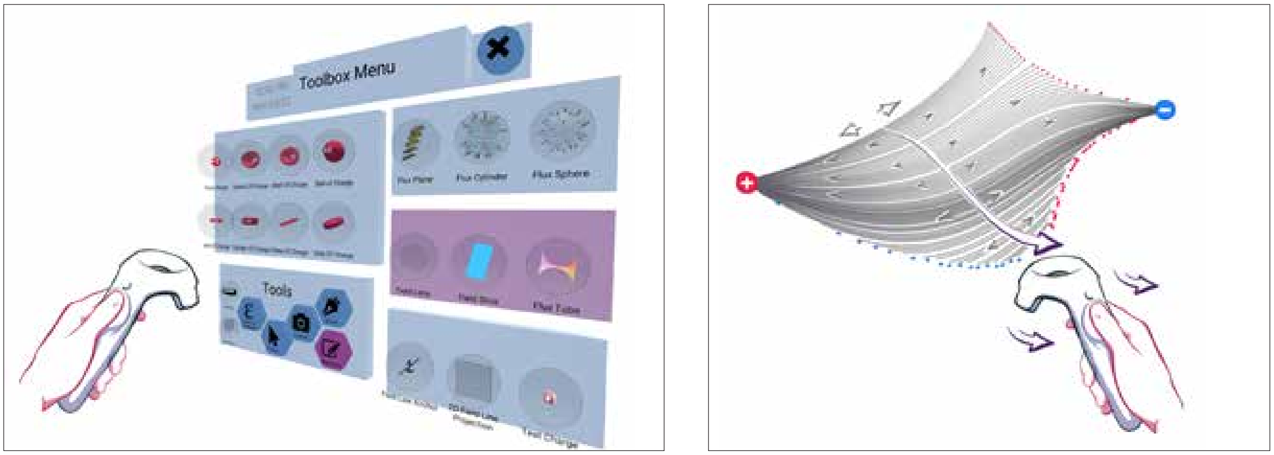
FIGURE 3

***A user creates five different charges**, one with a charge of +5 and five with charges of −1 (left). The user then starts a dynamic simulation that uses the Coulomb interaction, friction and a Pauli repulsive force, to evolve the position of the charges to a steady state (right). [Credit: Fields, Greenwald.]*

Electrostatic Playground: a playground for Gauss's law

The Electrostatic Playground project was begun in the summer of 2016 with the goal of providing intuitive understanding of the geometry of electric fields and the dynamics of inverse square law forces. The prototype allowed users to instantiate point charges with varying magnitude and sign; start and stop a dynamic simulation of multiple charges interacting through their Coulomb attraction and repulsion; and switch on and off a constant field (*Figure 3*). It also supported multiple users sharing the same physical and virtual space. The experience was highly compelling, and motivated the subsequent endeavor to use the technology in a more formal educational way.

We proceeded by soliciting input from a team of instructors for *8.02: Electromagnetism I*, Drs. Peter Dourmashkin and Michelle Tomasik. We demonstrated the technology to them and presented a set of constraints governing its practical usage in the context of residential education at MIT. Two of the most critical constraints were the way in which students would access the experience and the quantity of content that would be feasible to produce. Since the technology requires a dedicated space with devices installed, we knew student usage would need to be scheduled in small groups outside of class time. To make this effort worthwhile for students, we designed for longer, one-hour sessions. Next, we decided that as resources were not available to create companion VR experiences for the entire semester's curriculum, it was important to begin with one single concept or unit of maximal value. The 8.02 instructors agreed that Gauss's law was both challenging and likely to benefit from direct, 3-D representation.



Keeping in mind our priority on exploratory learning, we designed Electrostatic Playground around a "sandbox" model, where participants could instantiate any of a variety of charge distributions or visualization tools at will. Charge distributions included point charges, balls of charge, shells of charge, solid lines of charge, hollow lines of charge, infinite planes of charge, and infinite slabs of charge. Visualization tools included an open, square plane that displays electric field and flux at an array of points; a closed cylinder that shows electric field and flux at an array of points as well as the overall flux through the surface; and a sphere with analogous properties to the cylinder. Also available was a tool to create an individual field line anchored at a point in space, and a "field line generator" that allowed learners to sweep their hands through space to spawn families of field lines from points of their choosing (*Figures 4 and 5*). This set of tools was more than adequate for learners to assemble and tinker with systems that illuminated Gauss's law.

We soon discovered that while these tools in principle provide everything that is necessary to understand Gauss's law without some form of guidance, only a small number of students would be able to actually glean the intended insight.

FIGURE 4

A toolbox menu *allows the user to create charge distributions or visualization objects, and change controller-based tools (left). One example of such a tool is the Field Line Generator (right), which allows the user to explore field lines by sweeping the controller through space with the trigger pressed. [Credit: Greenwald, Corning, McDowell.]*

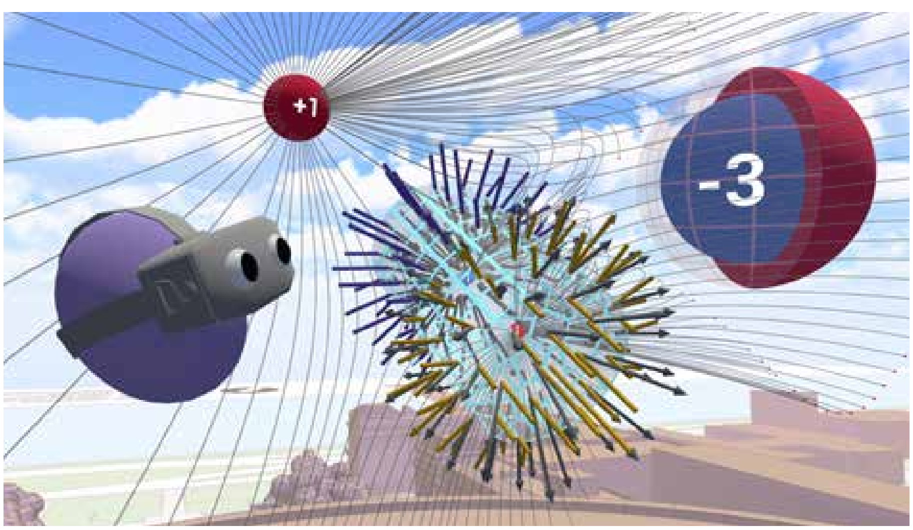


FIGURE 5

Using the toolbox*, users can assemble a wide variety of systems and explore their properties directly. The system shown here contains three point charges, a shell of charge, a ball of charge, and a cylindrical Gaussian surface. The field line generator tool has been used to selectively expose the geometry of the field. [Credit: Greenwald, Corning, McDowell.]*

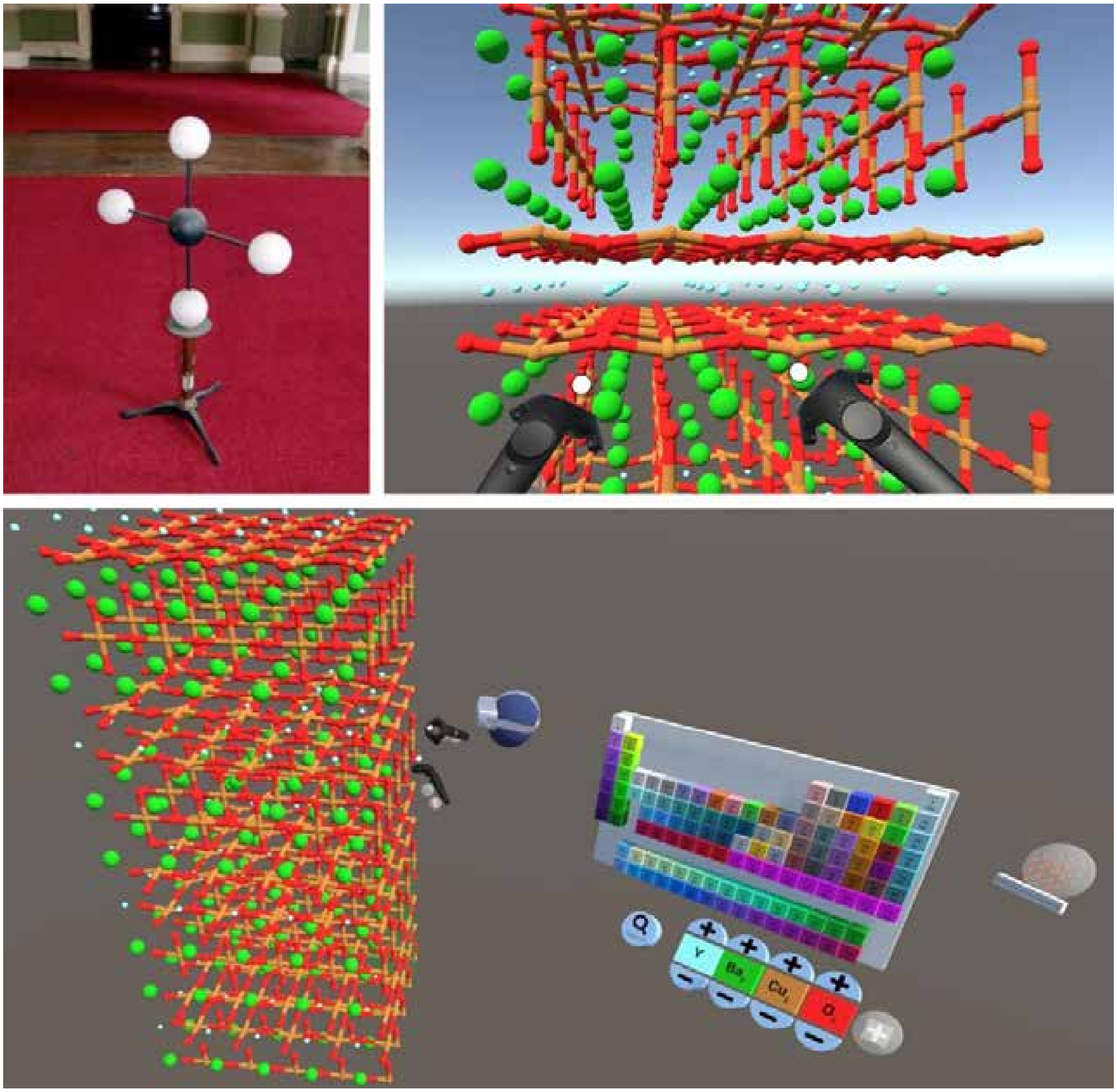
To counter this deficiency, we implemented VR's multi-user system to develop a model where instructors interact with students in real-time, using the sandbox to illustrate concepts in that instructor's own style. After a number of such pilots, we were able to assemble a lesson plan that would begin with the concept of charge and Coulomb's law, proceed through electric fields and flux, and finally arrive at Gauss's law.

To facilitate exploratory learning, we cycled through passive and active segments within the VR system. We settled on a roughly 10-minute cycle, with each segment including two to three minutes of narrative and ending with an "interlude" to suggest how a student might explore to understand the relevant concepts. To compensate for instructors' limited availability for one-on-one teaching for each student while using the VR system, we also constructed a way to "record" these live narratives for students to watch in the virtual environment in a self-paced way. Altogether, about fifty students piloted the experience, either solo, or in small groups of two to four; feedback was very positive. We are currently working towards a larger deployment at MIT and a formal study of the comparative effect of this technology on learning. Further, we are preparing a version of the application to be released publicly, for use by anyone with access to the appropriate hardware.

Crystal VR: visualizing crystalline matter in virtual reality for research, education and outreach

Our second VR project, Crystal VR [4], includes all of the explanatory and exploratory features developed in Electrostatic Playground, but with a distinctly different goal: to help the user understand and explore the structure of crystalline matter. Historically, visualization has played an important role in understanding the structure, physical properties and dynamics of materials. For crystalline solids in particular, understanding the positional relationships between atoms in the repeated unit cell offers insight into how a material will behave. However, crystals are three-dimensional objects, which makes their representation in textbooks challenging. This has led to the development of group theory representations and stereographic projections of crystals, which while capturing the information encoded in crystal structures, are rather abstract.

More direct visualization of structures with 3-D models can convey further, vital information about crystal structures. "Ball and stick" models (*Figure 6, top left*) were first developed and used for this purpose in the 19th century and continue to be developed—most recently in the form of 3-D-printed models. The disadvantage of such structures, however, is that they are limited in what they can represent (*e.g.*, all atoms must be physically connected), plus as a tool they are not easily modified. Computer visualization of models became relatively common in the 1980s; here the advantages compared to physical models are that there is no limitation on the structures that can be shown, and the entire catalog of known physical structures is readily available. While manipulation of such structures can be done via standard inputs, this is less natural than with physical models, and the projection of the image itself onto the 2-D screen limits their ability to convey their 3-D structure.



With Crystal VR, we have developed a VR environment for viewing crystalline structures and have found the use of VR offers the ability to borrow from the best aspects of both physical ball-and-stick models and standard computer visualization software: the models can be viewed and manipulated as in the case of the former, and are fully modifiable as in the latter (*Figure 6, top right*). Furthermore, connecting such programs to recently developed online databases of crystallographic information allows the direct importing of structures and information on an as-needed basis (*Figure 6, bottom*). VR also offers the possibility of simulating dynamics.

FIGURE 6

First "ball and stick" model *for methane by von Hofmann, c. 1860 (top, left). [Credit: Henry Rzepa and Royal Institution of London collection.] User's view using Crystal VR to inspect the high-temperature superconductor* $YBa_2Cu_3O_7$ *(top, right). View of user and material search interface in Crystal VR (bottom). [Credit: Greenwald, Checkelsky, Corning, McDowell.]*

Perhaps the most important element of crystal structures is their symmetries. These govern physical properties ranging from their allowed vibrational modes to their topological electronic properties. However, conveying the information

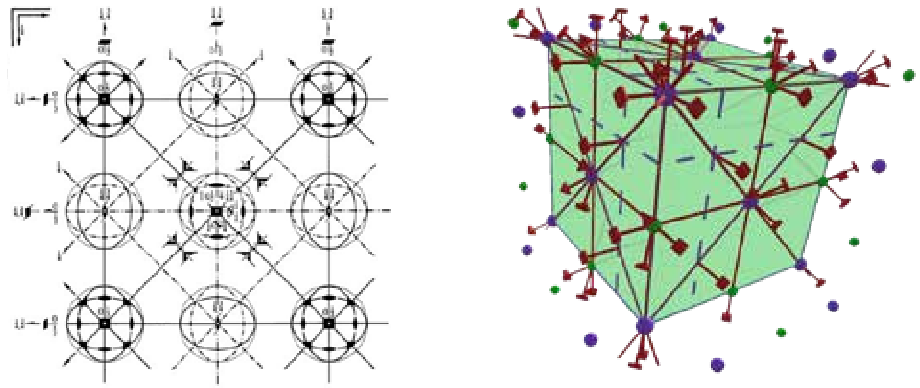


FIGURE 7

Symmetry diagram *for space group 225, to which the rock salt structure of NaCl belongs (left). [Credit: International Tables for Crystallography A, edited by Th. Hahn.] VR representation of NaCl symmetries (right). (Credit: Greenwald, Corning, McDowell.]*

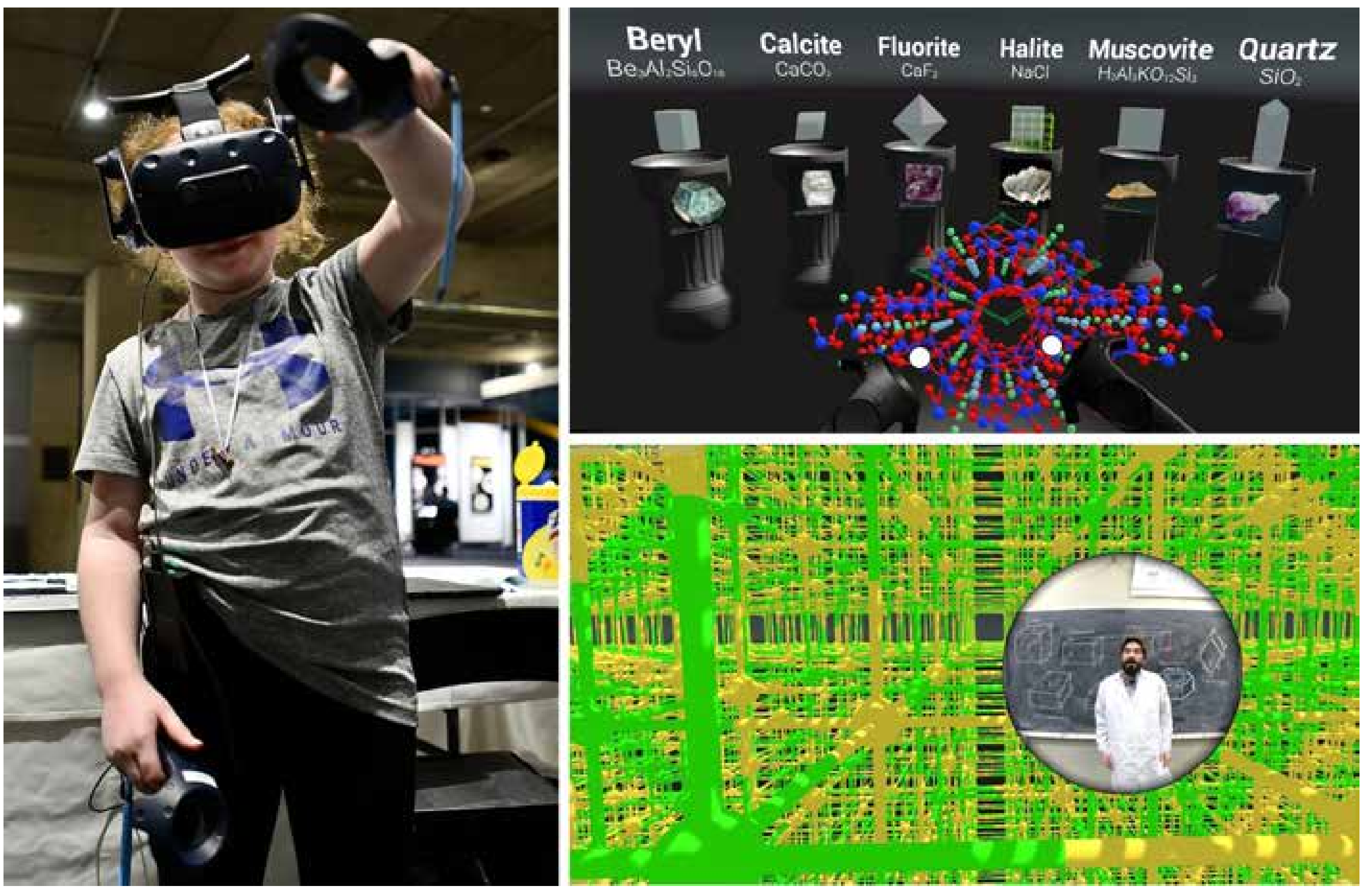


FIGURE 8

Interactive VR Exhibit*, Museum of Science, Boston (left). [Credit: Josh Reynolds for MoS.] Matching atomic structures to crystals from MoS Collection (top right). [Credit: MoS Collection.] View from inside a salt crystal (bottom right), with explanation from Checkelsky (inset). [Credit: Greenwald, Corning, McDowell.]*

about crystal symmetries carries many of the same challenges as the visualization of crystal structures themselves. The most common approach to visualize such information is through symmetry diagrams of the crystallographic space groups (*Figure 7, left*). To address this, Crystal VR implements the information of the international tables for crystallography in its 3-D environment (*Figure 7, right*). Thus, direct manipulation of symmetry elements and operations in VR offers an unprecedented connection between these abstract concepts and their visualization.

The lessons learned from previous development in both general education research and VR education research are ingrained in Crystal VR. For example, the sensorimotor interaction with objects to engage the student is a key element of the interaction in Crystal VR. Compared to standard computer programs in which a mouse or keyboard acts as the conduit for interacting with the structure, the use of VR allows direct manipulation and "hides" the technological conduit. The ability to create structures of scale immensely larger than what is possible with physical models allows a new regime of viewing the crystal from the viewpoint of the atom by immersing the operator in the atomic structure.

Crystal VR has found utility in a research context, while showing promise for lowering the barrier for entry to novices. Recently, Crystal VR was the centerpiece of a successful exhibit at the Museum of Science, Boston [5] (*Figure 8*), where participants with no prior training in crystallography were able to identify which real crystals belonged to different crystalline groups. Extending such activities in Crystal VR to interactive sessions with participants either co-located or remotely located offers an exciting opportunity for increasing the accessibility of these educational activities. Similarly, it has proven highly successful at the graduate education level in the Quantum Science Summer School [6].

Implementing VR for education and research: challenges and approaches

VR technology is still in its infancy, and its continuous, rapid evolution implies both steady improvement and a moving target for development and deployment. There are many considerations for any vision of the successful deployment of VR for education and research. Based upon our experience, we think the most challenging issue is the "authorship problem." That is, while it is easy to imagine myriad virtual worlds that would be beneficial for learning, there are both short-term and long-term obstacles to producing many kinds of virtual worlds. In particular, the choice of a high-level concept for the generation of content is tremendously important, and must be made with input from domain experts, educators and computer scientists. Imagine, for instance, the construction of physical buildings. Having at your disposal a saw, nails and wooden boards, it would be easy to imagine that any building could be constructed with sufficient time and effort. Yet, upon further inspection, these tools will fall short for building either a skyscraper or a Buddhist temple—and for different reasons. For our purpose, the software (architectural) approach is crucial in considering large-scale use of VR for education or research, and requires a wide range of input from a broad array of specialists.

Given that we have created a well-designed architecture with tools optimized for the domain, how do we then create content? We feel that multi-user, simulation-based, exploratory learning, coupled with a system for the creation and exchange of VR recordings, can serve as a basis for a large-scale content creation system. A simulation-based approach allows a wide variety of concepts to be illustrated in the virtual world, without additional programming, assuming the tools developed are versatile. This takes the programmer out of the critical path, as soon as a certain fundamental groundwork has been laid. Then the particular narrative and learning goals can be tailored by the instructor—custom-tailored to the age, native language and expertise of the designated audience. A single VR recording for a given target audience, once deposited in a global repository, represents a form of basic coverage for that audience that can be improved over time in subsequent revisions, and by different instructors. We can imagine, for example, electricity and magnetism taught in every language and at every skill level by using recordings on top of a simulation similar to Electrostatic Playground, but much broader in capabilities.

Moreover, the multi-user and recording capability solves numerous feasibility issues. Consider the interaction design problem: how exactly do learners interact with the learning content, and can this be made consistent across domains so as to minimize the cognitive overhead of learning how to interact, before being able to focus on the content? This problem is sure to be vexing for years to come, but in the meantime having a mechanism for experienced users to show novice users the ropes via "recording" is an excellent stand-in for a perfectly intuitive interaction design. The multi-user capability also allows remote experts to interact with students in areas where they may not have a qualified teacher. It will also allow students to find peer groups to learn with when there are none at their school. Most importantly, it allows students to actively collaborate in well-designed virtual worlds to develop their understanding and sense-making of physical systems.

Altogether, VR offers the prospect of collaborative learning and exploration at its best, and has enormous potential to impact both education and research in the near future.

NOTES

[1] Gauss's law states that the surface integral of the electric field over a closed surface is equal to the electric charge contained within that surface.

[2] Where did this technology come from, and where is it going? The development of the Oculus Rift VR headset, begun in 2012, inspired a number of large capital investments in VR technology by Facebook, HTC, Microsoft, Google, and Hewlett-Packard, among others. These companies continue to put enormous resources into the development of viable commercial VR products, such as wireless VR headsets with on-board computing power adequate for

6DoF exploration in VR, at increasingly consumer-friendly price points. For the two projects described here, we used HTC Vive headsets with powerful PCs and graphics cards.

[3] Supported by funding from the MIT Media Lab Consortium, Open Learning and HTC VR for Impact. MIT Media Lab and MIT Materials Research Lab collaborators include P. Maes, W. Corning, G. McDowell, G. Fields, E. Hong, A. Y. Wang, S. Gibson, M. Jamy, and T. Watson.

[4] The Crystal VR project is funded by the U. S. Air Force Office of Scientific Research (Grant #FA9550-18-1-0516), and supported by the work of Checkelsky group PhD candidates Aravind Devarakonda and Linda Ye.

[5] Led by Museum of Science, Boston, staff members Carol Lynn Alpert, Karine Thate and Megan Litwhiler.

[6] For more information on the National Science Foundation/Department of Energy/Air Force Office of Scientific Research Quantum Science Summer School, visit *qs3.mit.edu*.

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