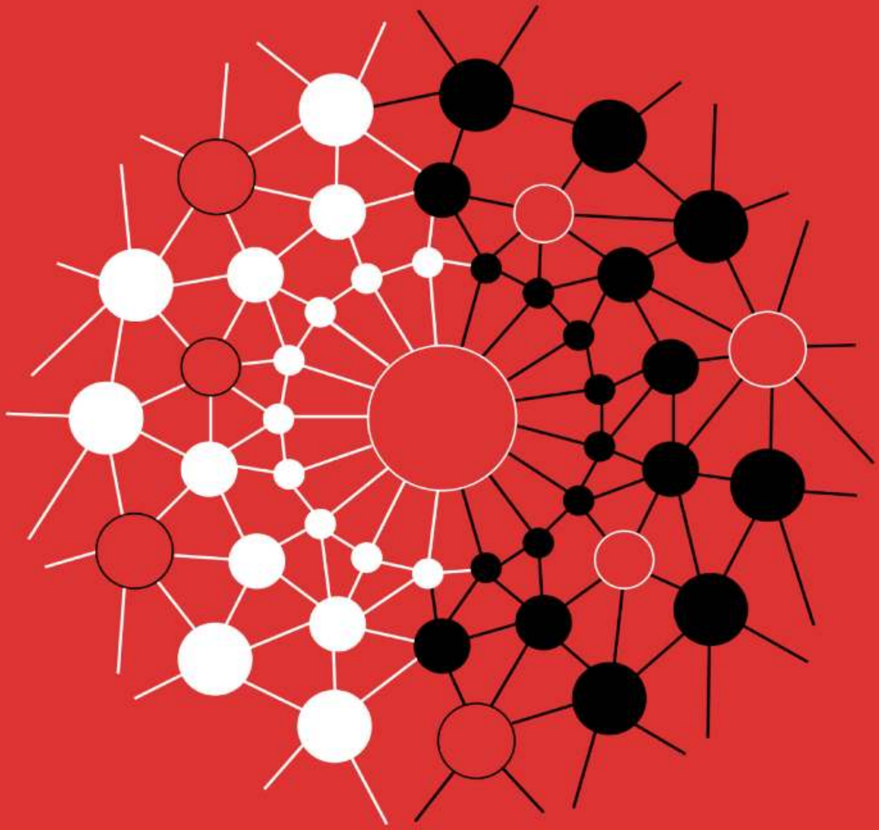

Cyberlearning Community Report:

The State of Cyberlearning and the Future of Learning With Technology

June Ahn, Jodi Asbell-Clarke, Matthew Berland, Catherine Chase, Noel Enyedy, Judith Fusco, Shari Gardner, Shuchi Grover, Erica Halverson, Kemi Jona, H. Chad Lane, Wendy Martin, Emma Mercier, Tom Moher, Amy Ogan, Nichole Pinkard, Joseph Polman, Jeremy Roschelle, Patricia Schank, Katie Headrick Taylor, Michelle Wilkerson, and Marcelo Worsley.

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Executive Summary

Cyberlearning researchers envision and investigate the future of learning with technology. As of summer 2017, the Cyberlearning and Future Learning Technologies (CFTL) program of the National Science Foundation (NSF) had made 279 research grant awards. In addition, several hundred other NSF research projects have cyberlearning themes. Many of these cyberlearning projects are in the exploratory stage or aim at capacity building, consistent with the goal of expanding frontiers. These projects typically do not aim to produce market-ready products or prove efficacy. Rather, the early results are often proof-of-concept designs, along with relevant theoretical insights and advances in methods.

Although specific research questions vary, in general the cyberlearning community is united around several fundamental questions:

- How can students use their bodies and minds to learn what will be important in the 21st century, such as collaboration, scientific argumentation, mathematical reasoning, computational thinking, creative expression, design thinking, and civic engagement?
- What advances in computation and technology are needed to design, develop, and analyze innovative learning experiences?
- How can learning with technology expand access, equity, and depth of learning across diverse people, institutions, and settings?

In their approach to answering questions like these, cyberlearning researchers express several commitments. Cyberlearning researchers are oriented toward a technical and educational horizon approximately 10 years in the future. Cyberlearning researchers believe that involving diverse people and perspectives in the early stages of research and design enables them to address equity issues. Cyberlearning researchers believe that learners develop their knowledge, skills, and identities across settings — not just as students in formal classrooms. Cyberlearning researchers believe that a good way to explore how people learn is by designing innovative technologies that incorporate findings from the learning sciences and experimenting with those designs in real-world settings. A way to better understand learners is to enable them to express themselves through making, programming, constructing, and inventing. Finally, the cyberlearning community aspires to be at the forefront of convergent science, an emerging approach to research that integrates different types of expertise and findings from multiple disciplines to address problems. Two key disciplines that researchers synthesize are the learning sciences and computer science.

Cyberlearning research is design research. Project leaders aspire to create general designs (sometimes called genres) that go beyond what is possible in today's products and illuminate visions of how learning can be enhanced with technology in the future. The authors of this report summarized six emerging genres:

Community Mapping	Using mobile, geospatial tools for learning in context at the scale of a neighborhood, community, or city
Expressive Construction	Computing as a creative literacy, focusing on students' expressiveness, ability to represent STEM ideas, and sharing of emerging understandings
Digital Performance Spaces	Immersive, participatory, social investigations of simulated scientific phenomena that appear to be occupying the entire space of the classroom
Virtual Peers and Coaches	Agents that use verbal and nonverbal communication to establish rapport with a student and thereby support engagement in explaining STEM concepts
Remote Scientific Labs	Students control real scientific equipment at a distance, learning about science with authenticity and support
Collaborative Learning with Touch Interfaces	Expanding collaborative learning via multitouch interfaces on tabletop, tablet and mobile computers

The authors also highlight how cyberlearning researchers are advancing methods to study and improve these learning designs, in particular:

Multimodal Analysis	Integrating multiple streams of data, such as audio, video, eye gaze, sensors, and clickstream data
Analytics for Assessment	Measuring student learning as they use games and other online experiences to inform teachers and increase learning across different types of experiences
User- and Community-Centered Design	Engaging users and community members in the design process to make learning tools more attractive, useful, and effective

These six design and three methodological innovations do not comprehensively summarize the research and development advances occurring throughout the cyberlearning portfolio, which includes projects that span the spectrum of lifelong learning and address learning of topics in science, technology, engineering, mathematics, and beyond. The full community is supported by the Center for Innovative Research in Cyberlearning, which seeks to amplify research impact, broker connections among projects, broaden participation in the work, and facilitate collaboration among cyberlearning researchers to tackle bigger issues than any single investigator or project can make progress on. More information on cyberlearning projects and the community is available at the circlcenter.org website.

Although the majority of projects have an exploratory or capacity-building focus, cyberlearning projects are already making an impact. In 2016, cyberlearning research was featured at a White House symposium on educational technology and in the US National Educational Technology Plan. Videos about cyberlearning research have received more than 55,000 views across 145 countries, and CIRCL collaborated with other resource centers on two annual video showcases of NSF-funded research that together attracted about 50,000 participants. And scientists are publishing findings about how students can learn challenging content with the support of emerging technologies – findings that are needed to guide the future of learning technology. One example of many findings discussed herein is that students learn more from games when bridging activities connect implicit learning with the game to formal, explicit classroom instruction – a connection that can be made stronger when learning analytics measure student progress in learning from their actions in the game.

Cyberlearning researchers strongly value the unique emphasis in these NSF awards on forging paths for computer scientists and learning scientists to work shoulder-to-shoulder on problems that are challenging and important to both expertises – and most projects are not only forging such relationships, but also training graduate students for future participation in convergent science. The authors observe a strong potential for increased impact in the future as cyberlearning engages with four of NSF's themes for the future: Harnessing Big Data, Exploring Human-Computing Frontiers, Increasing Inclusion of All in STEM Learning, and Strengthening Convergent Science. Strong commitments to equity, innovation, multidisciplinarity, and designing for the future are creating opportunities for the cyberlearning research community to provide essential design, methodological, and theoretical insights that will guide the future of learning with emerging technologies.

**Learners interacting in the
New York Hall of Science Connected Worlds exhibit.**

Used with permission of Stephen Uzzo.

Introduction

Cyberlearning researchers envision and investigate the future of learning with technology. In an earlier generation of research, the theoretical focus was on students' reasoning, the standard technology was a laptop or desktop computer, and the typical setting was a conventional classroom. Such research remains tremendously important. However, emerging frontiers in the learning sciences now call on cyberlearning research to develop new theories, investigate developing technological capabilities, and consider diverse education settings. Here are some of the frontiers of cyberlearning research:

- Learning science researchers are paying more attention to affect and emotion, to students' developing identities, to discourse and gesture, and to embodied cognition.
- New technological designs for learning incorporate sensors, immersive experiences, augmented reality, big data, speech recognition, touch interfaces, and circuits embedded in fabrics and other forms of digital fabrication.
- Additional education settings include community-scale learning, specially designed places and spaces, multiplayer gaming environments, and virtual worlds.

Earlier generations of school technology (such as graphing calculators) were designed based on an understanding of how people learn (e.g., providing multiple representations) and have led to widespread and positive effects on education (Roschelle, Noss, Blikstein, & Jackiw, 2017). The existing research base remains vital. Yet investigating new research questions concerning emerging technologies and contexts is imperative so that a useful body of research-based knowledge is available to guide learning with new technologies when they become commonplace in 5, 10, or 20 years.

An example of learning research with an emerging technology in a novel setting is the *Connected Worlds* exhibit a multidisciplinary team at the New York Hall of Science created using wall-sized screens to display biological niches within a larger ecosystem. Visitors can learn how water affects the life in an ecosystem by gesturing near the screens to create life forms and by redirecting flows of "water" on the floor. The *Connected Worlds* exhibit enables embodied learning in an immersive space with a variety of sensors. The learning process is directed by the visitors' own interests rather than a formal curriculum. The exhibit successfully engages multigenerational groups of learners, such as children with parents and grandparents, from diverse cultures and backgrounds. *Connected Worlds* has also become a research site for scientists who are pushing the frontiers of multimodal analytics — that is, the study of learning with data streams that include physical movement, sound, and logs from interactions with technology (as well as more traditional observations).

What is Cyberlearning Research?

Cyberlearning research is the study of how new technologies, informed by what we know about how people learn, can be used to advance learning in ways that were never before possible. Researchers have found that the best way to investigate potential advances is to design learning experiences and study them. Thus, cyberlearning research is creative and aspirational and often features novel designs. Cyberlearning research is also grounded and empirical. It involves frequent testing of designs in realistic settings (such as a museum, a playground, or a school). Using the findings from testing, cyberlearning researchers improve their designs and clarify theories of learning. Given that the possibilities for the future are vast and divergent, the best way to describe the growing body of research knowledge is to organize it according to classes of designs (genres) and methods. For example, what we learn from studying how children interact with a robot that speaks Chinese may be different from what we learn from groups of learners engaging collaboratively in the immersive *Connected Worlds* exhibit.

As of summer 2017, the Cyberlearning and Future Learning Technologies (CFTL) program of the National Science Foundation (NSF) had made 279 research grant awards. In addition, several hundred other NSF research projects have cyberlearning themes. Many of these cyberlearning projects are in the exploratory stage or aim at capacity building, consistent with the goal of expanding frontiers. These projects typically do not aim to produce market-ready products or prove efficacy. Rather, the early results are often proof-of-concept designs, along with relevant theoretical insights and advances in methods. Demonstrating impacts on conventional education measures is rarely the primary intent in cyberlearning research, especially because today's standardized tests are often ill suited to assessing what learners are achieving in these new environments. Thus, the research is conducted in stages, with measures of impact becoming a higher priority as the new designs become ready for wider use. Some of the mature learning designs described in this report have demonstrated positive impacts on measures of learning, motivation, and interest in science, technology, engineering, and mathematics (STEM), and some are leading to products, as described in the From Project to Product sidebar on page 61.

> Cyberlearning research is grounded and empirical -- involving frequent testing of designs in realistic settings and improving the design and theory based on findings.

Leaders of these projects have convened annually for the past 5 years at NSF-sponsored cyberlearning community meetings. As a result of these meetings, a multidisciplinary community of researchers has formed with strengths in both technology and learning science. Although specific research questions vary, in general the cyberlearning community is united around several fundamental questions:

- How can students use their bodies and minds to learn what will be important in the 21st century, such as collaboration, scientific argumentation, mathematical reasoning, computational thinking, creative expression, design thinking, and civic engagement?
- What advances in computation and technology are needed to design, develop, and analyze innovative learning experiences?
- How can learning with technology expand access, equity, and depth of learning across diverse people, institutions, and settings?

This report was written by a group of researchers from this community who met over a year to discuss how cyberlearning research is addressing these questions. The field of cyberlearning is new, so these authors do not claim to present a consensus opinion. They are reporting on their perspectives. The three core purposes of this community report, which is intended to be the first in a series of reports, are

1. To inform researchers and the public about what cyberlearning research is and illustrate what cyberlearning projects look like.
2. To highlight findings that are indicative of what cyberlearning research can contribute.
3. To connect this body of work to broader educational visions and strategies, indicating where it may find its eventual greatest impact.

What Makes Cyberlearning Research Distinctive?

Cyberlearning research is not easily categorized because it embraces a wide variety of ideas and approaches. Yet when the authors first came together, they readily identified a core set of goals, purposes, and practices that the community is committed to and that make cyberlearning projects distinctive. Here are the key commitments.

1 **Oriented toward the horizon.** Cyberlearning researchers are oriented toward a technical and educational horizon approximately 10 years in the future. Projects sometimes involve mature technologies used in innovative ways, but they also can involve emerging technologies such as virtual reality or wearable computers that may become ubiquitous in the future. Rather than waiting for wide adoption, cyberlearning researchers are already exploring how these technologies can help future learners.

2 **Focus on equity.** Understanding how technology can enhance learning for the less privileged in our society is central to many cyberlearning projects. History has demonstrated that technologies can provide unprecedented educational opportunities, but they can also exacerbate inequalities if we do not consider the realities of different communities' access to and experience with technology. Cyberlearning researchers believe that involving diverse people and perspectives in the early stages of research and design enables them to address equity issues.

3 **Learning as a cross-context community endeavor.** Cyberlearning researchers believe that learners develop their knowledge, skills, and identities across settings — not just as students in formal classrooms. Learners move across boundaries in space and time and interact with a wide variety of people and places. While some cyberlearning research concentrates on the individual learner, much of the research investigates a community of learners.

4 **Research through design.** Cyberlearning researchers believe that a good way to explore how people learn is by designing innovative technologies that incorporate findings from the learning sciences and experimenting with those designs in real-world settings. Cyberlearning researchers also use new technologies and learning science theories to create innovative approaches to data collection and analysis. For example, a researcher might use mobile devices to collect data on how youth move through multiple environments in order to understand how youth learn across a sequence of real-world interactions in different places.

5 **Youth voices.** Cyberlearning researchers conceptualize learners as complex young people with wide-ranging interests and experiences rather than primarily as students in schools, participants in programs, or visitors in museums. A way to better understand these young people is to enable them to express themselves through making, programming, constructing, and inventing. Many cyberlearning projects use such hands-on techniques to explore how innovative technologies can document, encourage, and amplify youth voices.

6 **Convergent science.** The cyberlearning community aspires to be at the forefront of convergent science, an emerging approach to research that integrates different types of expertise and findings from multiple disciplines to address problems. Two key disciplines that researchers synthesize are the learning sciences and computer science. Using the learning sciences, they develop theories of learning and methods for investigating learning that can guide design and research. Using computer science, the researchers develop perspectives, methods, and tools that spur technological innovation. Researchers' orientation to convergent science allows cyberlearning research to make several contributions to society: (1) tackling deep, complex problems that promise to improve learning in the future; (2) connecting scholars across fields to develop new bodies of knowledge; and (3) through partnerships, seeking impact on practices, policies and products that shape teaching and learning.

Historical Roots of Cyberlearning

A long tradition of research is exploring how emerging and futuristic technologies could improve human cognition and learning. The earliest research in education technology continues to influence cyberlearning research today. Although a full history from the 1960s to the present is beyond the scope of this report, we offer some examples that illustrate the continuities over decades of research and innovation:

- **Frontiers of Human-Computing Interaction.** In 1969 Douglas Englebart gave what is now referred to as "The Mother of All Demos" in which he demonstrated how cognition could be augmented through human-computer interaction breakthroughs such as the mouse and networked collaboration. Although the field has moved beyond the mouse to multi-touch, sensory, gesture, speech, and other forms of interaction, investigating how emerging capabilities can enhance collaboration and learning remains central to cyberlearning research.
- **Computational Thinking.** In 1972 Alan Kay described how a tablet computer could lead to a range of transformative learning experiences in his paper on the "dynabook." Kay anticipated today's widespread uses of tablet computers for learning and also set the stage for considering how "computational thinking" broadly influences how people learn (Kay, 1972).
- **Learning Analytics and Adaptive Learning.** In 1972 Alan Newell and Herbert Simon published *Human Problem Solving,* a seminal volume that connected human cognition with artificial intelligence (AI) techniques and models, eventually leading to a strong program of research on "cognitive tutors" and "intelligent tutoring systems" that continues to this day (Newell & Simon, 1972). The AI and education aspects of cyberlearning today are featured in work on learning analytics (and the related education data mining), as well as in the evolution of the intelligent tutor paradigm to new adaptive or personalized learning approaches.
- **Learning at Scale.** Starting in the 1960s, the University of Illinois developed PLATO, the first general-purpose computer-assisted learning system. In the 1970s, PLATO was supported on thousands of mainframe computers and terminals around the world. PLATO pioneered such features as forums, message boards, online testing, and multiplayer games that are prominent in more recent massive online open courses (MOOCs) — and PLATO remains available as a commercial product. Today's learning- at-scale research builds on this tradition but benefits from the ubiquity and bandwidth of the Internet, dramatic increases in data capture and analysis capabilities, and the evolution of user interaction paradigms.

◆ **Constructionism, Makerspaces, Fab Labs, and Scratch.** Building on more than a decade of exploratory research, Seymour Papert (1980) published *Mindstorms*, presenting a vision of learning as the construction of knowledge that happens most effectively when people construct artifacts or objects and then talk with others about them to improve them. Much of Papert's work was in technology-rich environments. (Indeed, he was co-inventor of the Logo programming language.) However, he was careful to keep technology in the service of learning. This seminal work led to ongoing research through the 1990s to today's makerspaces and Fab Labs (environments for open-ended tinkering and creative production) and the massive impact of Scratch as a kids' coding tool. Many scholars have observed that the historic beginnings of Papert's Logo were with a programmable robot (the turtle), and we are now returning to activities where students construct computational solutions for controlling robots, fabrication machines, and other physical devices.

As important as these continuities are, it is equally important to recognize the opportunities to leverage discontinuities introduced by technology. Historically, as the input and output methods of technology change, radically different approaches to learning become possible. For example, one of the long-standing successes in learning technology has been dynamic geometry (dynamicgeometry.com), an approach to exploring geometry by allowing a learner to transform a diagram interactively. In retrospect, we see that the mouse enabled continuous change as an input and digital displays enabled continuous transformation of a geometric figure as an output. The tangible connection between moving a mouse and changing a shape turned out to be powerful for learning geometry. Today, the evolution of dynamic approaches to mathematics learning may further evolve, for example, to include 3-D input and output, handwriting recognition (important for mathematics symbols), speech recognition, and other new capabilities of technology that are relevant to how people learn mathematics.

Advances in learning theory also drive innovation. For example, in cyberlearning research a newly energized emphasis on embodied learning (the idea that people learn through physical as well as intellectual engagement in the world) makes research with sensors of bodily motion more relevant. Likewise, an emphasis on community-based learning makes research with geospatial mapping tools more important today. Overall, the recent explosion of both learning sciences and technological advances makes it important to press forward to new horizons rather than just investigate applications of today's most common technologies and learning approaches. The horizons are multidimensional, including new user interface technologies (such as augmented reality), data analysis capabilities (learning analytics), and newly important learning research areas (embodied cognition, cognitive neuroscience). The push to new horizons involves both asking learning research questions that could not be investigated as deeply before and seeking technical advances that can be shaped to better support the processes of human learning.

Illustrative Cyberlearning Designs

> *The cyberlearning community is unique in its integration of deep consideration of learning science, high-risk innovation in technology, and rigorous educational research. It is this work that lies at the intersection of these three fields which gives the most promise for truly transformative research. The community is both collaborative (outward thinking) and visionary (forward thinking) — and thus drives the agenda for future and novel research.*
>
> —Jodi Asbell-Clarke, EdGE at TERC

Cyberlearning research is design research. Project leaders aspire to create designs (sometimes called genres) that are innovative (not already typical in existing products) and also serve as examples for broader visions of how learning can be enhanced with technology. A general design is one that has the potential to open up opportunities for many specific learning resources and thus could lead to many products. This section highlights six types of general designs created by cyberlearning researchers each of which draws on convergent innovations in the learning sciences and computer science. Following the description of these six genres, the next section highlights three complementary advances in research methods.

We use examples of projects to illustrate how these designs and methods are integrated into education environments. The descriptions clarify how the projects required convergent science — the engagement of learning scientists, computer scientists, and researchers and practitioners in other fields. Each example also shows how these projects can push the frontiers of learning theories and computing technologies. The report authors and editors selected these projects as illustrative; they are not inclusive of all innovative designs developed through cyberlearning research. Other examples can be found on the Center for Innovative Research in Cyberlearning (CIRCL) website (circlcenter.org). Also, future community reports will cover additional genres and methods.

1. Community Mapping: Moving and Discovering Across Contexts

By Katie Headrick Taylor and Nichole Pinkard

Design Description, Motivation, and Conjectures

The essential insight in this genre is that youth can learn by creating digital maps of their communities and by using digital maps to navigate learning opportunities in their communities. By investigating digital mapping technology, cyberlearning projects are transforming the way learners, their families, and educators are interacting across home, school, and neighborhood. Advances in a range of location-aware and mobile technologies have made it easier than ever for learners to capture data about their neighborhoods and explore their communities (e.g., Mamdani, Pitt, & Stathis, 1999; Townsend, 2013). Locations and paths from GPS, video, photos, text, and demographics are just a sample of the data accessible for scientific analysis of a learner's community. Cyberlearning researchers have designed innovative ways to create experiences that enable learners to investigate personally meaningful issues related to their local communities.

Further, researchers are exploiting advances in mobile and location-aware technologies to investigate how learning happens as individuals actively move across settings and make sense of their movements and environments. What do these cross-context interactions with people and place look like? How do they help learners? How can we use the data generated from moving across settings to further enhance learning? As mobile use of digital maps expands, answering these and related questions will have increasing importance.

- **Computer science innovation:** Mobile computing with geospatial data visualization for nonprofessionals
- **Learning science innovation:** Learning in context at a community scale

Equity is an important focus of research on learning via mapping. To develop equitable learning opportunities for young people, educators and designers must have a deep understanding of the communities they live in (e.g., Leander, Phillips, & Taylor, 2010; Nespor, 1997), including the community assets they can access (such as libraries, parks, schools) and how the community might be improved (e.g., better bus routes, more sidewalks). As Dewey (1934) remarked in *Art as Experience,* "The first great consideration is that life goes on in an environment, not merely in it, but because of it, through interaction with it" (p. 12). The knowledge and skills available to students in their homes and communities have been described as "funds of knowledge" (Gonzalez, Moll, & Amanti, 2005) and the "geography of opportunity" (Tate, 2008). These have implications for teachers in schools as well as informal educators in libraries, museums, and out-of-school programs. In short, it is important for educators to have accurate information about the contexts the learners they serve come from so they can design instruction that is relevant to the learners' lived experiences.

Examples of Community Mapping

Current cyberlearning projects offer participants opportunities to take meaningful action in their communities. These opportunities address "mediated democracy," countering a concern that technologies insulate us from productive engagement with others (Rose-Stockwell, 2016; Taylor & Silvis, 2017). With new cyberlearning designs, learners from underrepresented groups can find grassroots solutions to challenging problems. Geospatial applications on mobile devices are particularly appropriate for collecting and analyzing local data (with residents, shopkeepers, and other community members) to create evidence-based arguments and recommendations for local improvements.

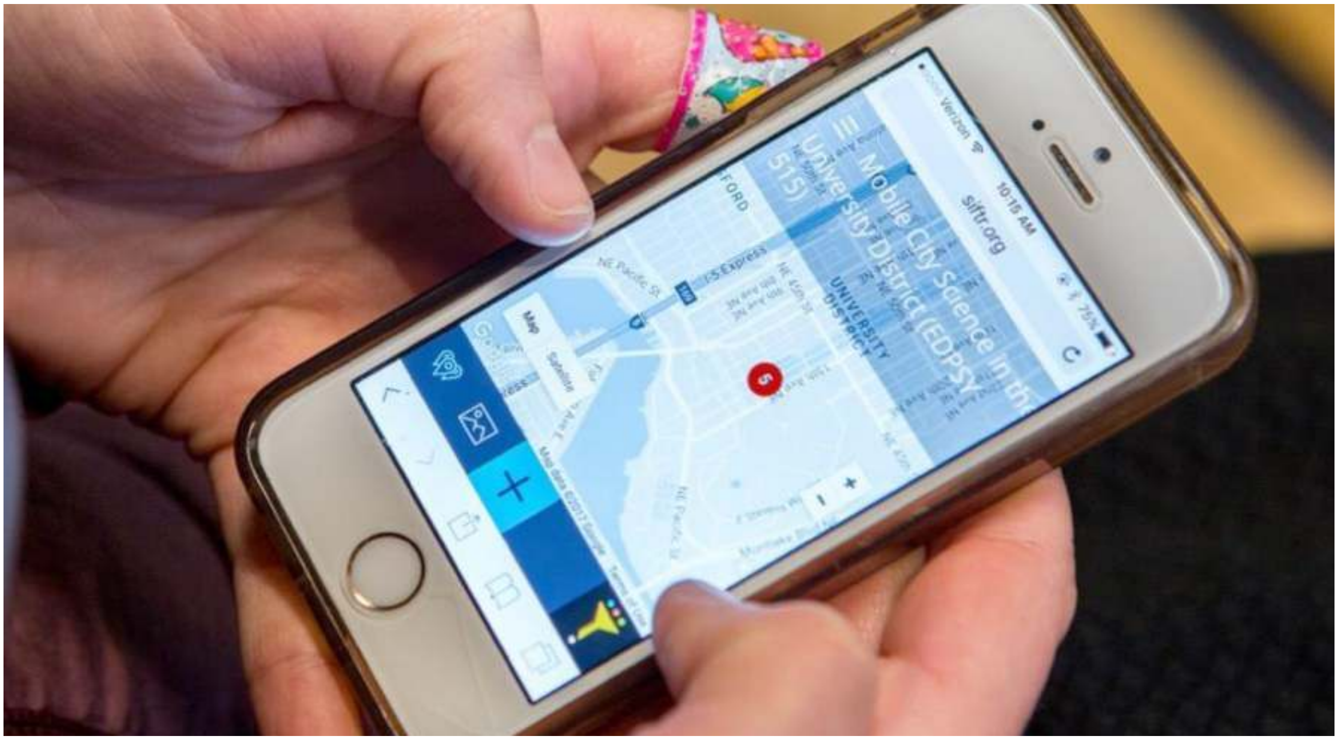
Nichole Pinkard's **Cities of Learning (CoL)** (NSF #1341974, #1441057) promotes the idea that learning and teaching occur everywhere, in museums, homes, libraries, community centers, and in the other cultural and historical assets urban settings have to offer. CoL provides a digital platform that aggregates, maps, and describes the learning resources available to young people in a given city (such as Chicago, Dallas, and Pittsburgh). What is more, CoL looks at the pathways young people take *between* locations so that moving through the city becomes its own form of learning, which is especially relevant to mobile technologies. As young people move along a given pathway in a city, CoL can alert them — and the adults who are invested in their learning — about other learning opportunities along that route. The digital platform also motivates students by giving badges to acknowledge young people's accomplishments and skill development as they move across settings.

Another important community-centered component of CoL is that it promotes *intergenerational* learning. CoL activities have been designed to connect young people with adult community members to discuss local issues. As youth talk with adults in their community, learning expands to occur both in and out of school. Adults in the community can mentor youth on their projects, providing perspective and insights that complement learning in school.

The CoL project identifies opportunities and resources for learning that already exist in communities and also reveals gaps. Hence, this work has helped to inform policymakers and program developers about where learning resources are lacking so they can target programming for those areas.

An example of a new resource that was developed is Katie Headrick Taylor's **Mobile City Science (MCS)** (NSF #1645102). MCS is a curriculum that provides youth with innovative mapping and tracking tools that helps young people collect, analyze, and argue from spatial and digital data they collect in Bronzeville in Chicago and Corona in Queens, using location-aware and mobile technologies. Young people participating in MCS are generating first-person and collaborative accounts of living in these communities, and also imagining what

A student uploading place-based data to the Mobile City Science Siftr™ site.



Used with permission of Katie Headrick Taylor.

they could become from a youth perspective. Designed activities such as historic neighborhood geocaches, mobile augmented reality walking tours, and countermapping provide novel learning experiences for youth, and also “expand adult-centric notions of civic agency and develop participatory mapping practices that elicit young people’s knowledge on their own terms” (Gordon, Elwood, & Mitchell, 2016, p. 2). Based on what is being learned with MCS, the Digital Youth Network and the New York Hall of Science are embarking on additional curricular designs to make their programming more compatible with the resources already in their communities.

One goal of research with MCS is to uncover how youth can develop a new kind of civic literacy for participating in community-level problem-solving, based on their skills in using mobile mapping technologies. The current design study is examining how two groups of urban youth collect data about important places in their communities (e.g., library, community center), obstacles to learning (e.g., no safe routes to school), and new learning opportunities (e.g., a developing community garden) using mobile and location-aware technologies. Futher, the work is discovering how the youth use the resulting maps to make evidence-based arguments for how to improve their communities. Educators are also using the resulting maps and data, to better understand the places students live. Insights from the maps and data are enabling educators to create more meaningful curricula and personalize educational experiences to the young people they teach.

Contributions, Challenges, and Opportunities

By harnessing mapping and location-aware technologies, this learning genre is making important contributions to computer science, learning science, and larger education communities. In computer science, research is contributing insights into how the interfaces of digital tools can make it easier for learners to build (and not just use) maps. In the learning sciences, this research is driving researchers to understand the role of context in learning. More broadly, the research suggests how maps can help learners continue learning as they move among different community resources and institutions.

By putting mobile mapping in the hands of youth, computer science researchers can gain a better perspective on how location data translate into meaningful visualizations for nonprofessional users of geospatial information. By analyzing how and what participants learn about complex community issues from being on the move through neighborhoods with mobile and location-aware technologies (Taylor, 2017), researchers can develop theories of *embodied computing* (the use of physical objects or actions to interact with the digital world, e.g., Alibali & Nathan, 2012; Farnell, 1999; Glenberg, Gutierrez, Levin, Japunitch, & Kaschak, 2004; Goldin-Meadow, Cook, & Mitchell, 2009). By helping researchers understand how young people actually interact in and make sense of their environments, projects like CoL and MCS can produce the information necessary for program designers to create innovative ways to involve young people living in underserved urban areas in their communities. These projects provide accessible, digitally mediated ways for youth-serving organizations, community developers, and/or social science educators to engage young people in civic

Students collecting geo-tagged data in the neighborhood using their mobile phones during an MCS activity.

Used with permission of Katie Headrick Taylor.

processes and conversations happening at the scale of the city. These studies will contribute to a new theory of social change whereby technologies democratize (rather than balkanize) learning and participation (e.g., Blikstein, 2013; Resnick, Berg, & Eisenberg, 2000; Wilensky & Papert, 2010) in community development processes to include young people's data-driven perspectives in planning and policy implementation (Taylor & Hall, 2013).

This design also comes with a range of methodological, conceptual, and ethical challenges that must be addressed. First, when the phenomena of interest are mobility and learning across settings, traditional place-bound research methods are not adequate. To date, researchers have relied heavily on wearable cameras to capture learning on the move through community spaces, but these often produce unreliable audio records and/or odd perspectives on the action (wearing a camera on one's head can skim the interesting activity out of the frame), not to mention vast amounts of video data to process and analyze. Researchers have to think of new ways to find meaning in the data produced by young people moving physically and digitally through urban and natural environments (Marin, 2013; Taylor, 2017). Another concern is the ethics of tracking youth as they move around their communities. Researchers need to ensure that youth and their parents/guardians are fully aware that such data are being collected and that they can set limits on when, where, and for what purpose any tracking data are collected and stored.

Current and future research on these learning designs will have important implications for efforts to improve communities' technological infrastructure, such as NSF's Smart and Connected Communities program. The Smart and Connected Communities program funds projects that investigate how digital tools can provide layers of information that improve community life, but the projects often have focused on energy or transportation issues, not on learning. These cyberlearning projects raise awareness of learning as a community-wide issue and push educators and designers to use technology and digital media in ways that foster empathy and consensus building for live community problems that involve learning. These projects also shift power relations in that the voices and interests of underrepresented people, such as youth, gain legitimacy in community conversations and in community development processes. Looking more broadly, creating and arguing from data produced with mapping technologies could constitute an emerging civic literacy. If so, developing this literacy would enable youth to influence change in their communities.

Resources

CIRCL Primer: Smart and Connected Communities for Learning: http://circlcenter.org/sccl

Cities of Learning Overview: https://vimeo.com/146527352

Mobile City Science: http://stemforall2017.videohall.com/presentations/876

DYD CAN: Engaging caring adults in youth STEM learning:
http://stemforall2017.videohall.com/presentations/939

2. Expressive Construction: Enabling Learners to Represent Powerful Ideas

*by Matthew Berland, Erica Halverson, Joseph Polman,
& Michelle Wilkerson*

Design Description, Motivation, and Conjectures

New technology tools are enabling more people to create things on their own or in groups. For example, broad populations have become engaged in the maker movement, in learning to code, and in using digital videos and other media to express ideas and share them publicly. Education research has made us more aware of the value of interest-driven activities as pathways to STEM college and career opportunities. However, constructive activities are not always deep learning activities. Hands-on is not always minds-on. A toolkit for making something does not always include tools for making sense of important concepts. And talking while making often does not rise to the level of learning by collaborating. This leads to a provocative research question:

> **How can we maximize the opportunity to learn within the opportunity to create?**

◆ **Computer science innovation:**
Computing as a creative literacy, open to a wide variety of interests

◆ **Learning science innovation:**
STEM learning grounded in expressive representations that youth construct

Through cyberlearning research, experts in collaborative, constructionist learning have come together with experts in computing-as-a-creative-literacy to create a new class of activities to deepen learning. Three key conjectures are driving a range of research projects:

1. that the **expressiveness** that arises with literacy in new media can be more closely tuned to learning processes (and not just processes of building things),
2. that **representations** should be designed to be supportive of learning important ideas (and not just getting things to work), and
3. that supports for **collaboration** can be designed to help learners to share how they make sense of key ideas as they build things.

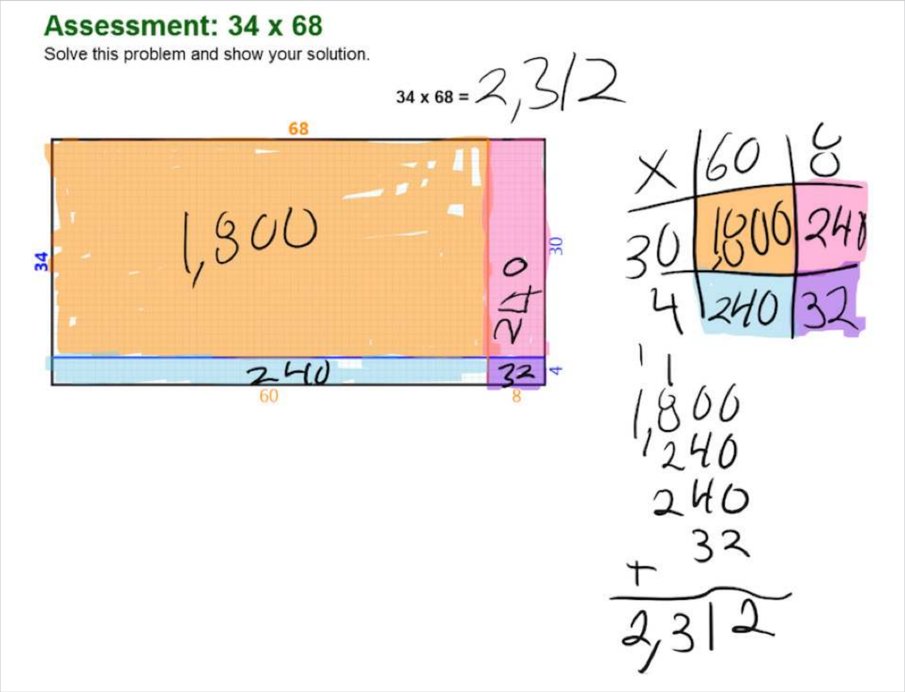
For example, researchers on the project **INK-12: Expressive Digital Tools for**

Elementary Math Education (NSF #1019841, #1020152) developed tablet and pen-based tools for elementary school children to show and share mathematical reasoning. The tools enable students to express reasoning using a combination of hand-drawn images and digital manipulatives. In this example, the student used an array tool to create the image and annotated and shaded it with the pen, using color to make the connection between parts of the array and parts of the calculation. In a classroom, students can develop different solutions to the same math problem on their tablet computers and wirelessly share them with the teacher, who can choose a variety of mathematical representations to discuss with all the students, and thereby enriching their understanding of mathematical concepts.

The ideas of expressiveness, representation, and collaboration in INK-12 and many other cyberlearning projects draw on earlier educational research. For example, many readers are likely to be familiar with Papert's work on constructionism (1980). Papert studied learning through situations such as programming a robot, called a turtle, to draw complex images by combining mathematics and art. He developed a theory that describes how learners build and refine knowledge through the active construction of sharable artifacts and the use of "powerful ideas" in mathematics, science, and computing.

Current work continues to develop constructionism and also brings in ideas about learning in communities of practice (Lave & Wenger, 1991) that emphasize the social side of learning — for example, the importance of discourse to making sense of complex ideas. Another strand of research concerns the idea that new media are giving rise to new literacies (diSessa, 2001; Gee, 2015) — such as literacy associated with computational thinking or with gaming. This confluence of research traditions also leads to asking research questions about

Using INK-12, a student solves a multiplication problem with a mix of shapes, color, tables, and symbols. The orange color, for example, highlights how the same information is in the sketch and in the table.



Assessment: 34 x 68

Solve this problem and show your solution.

34 x 68 = 2,312

x	60	8
30	1800	240
4	240	32

```
 1,800
   240
   240
+   32
 2,312
```

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how giving students agency and voice is important to learning:

- How do youth and adults exercise agency in seeking to change their worlds?
- How can they express their voices through new forms of inquiry, civic participation, and artistic expression?
- How does allowing more room for agency and voice make learning more active and more successful?

What is different today from earlier research is the usability, availability, and scalability of technologies for building things, for example in the maker movement. Whereas an earlier computational literacy would have been confined to expressing things at a keyboard in front of a computer monitor in a special lab, there now has been a dramatic increase in the modes of expression students can use to communicate, including not only typing and pointing with a mouse, but also gesturing, touching, speaking, sketching, and many other modalities. Moreover, the available computational devices are more diverse — far beyond conventional computers with a keyboard and screen — and the devices are more affordable and more widely available at school and in communities.

Thus student choice among constructive learning opportunities is expanding. Students can express ideas by programming a robot, and may do so in an intergenerational setting where they are supported by peers, older students, and adult experts. If they do not like making robots, students can build musical instruments, computer games, or clothing with wearable interactive electronics, again often with mentoring by an enthusiastic knowledgeable adult. Learners can take the role of journalists or citizen scientists who use data visualization, digital art, and simulations to communicate about their world. Youth may develop their ability to express ideas with technology in activities at schools, museums, community centers, or outdoors.

In general, a future of new learner possibilities is being created by three major trends: (1) a broader range of ways to interact easily with computational objects; (2) wider public access to powerful programmable tools previously limited to small, specialized communities; and (3) broader access to supportive settings in which learners can use these tools while meeting and talking with practicing engineers and scientists who can mentor their learning. To realize the value of these trends, cyberlearning researchers are investigating how expressiveness, representation, and collaboration can lead to deep, long-lasting learning.

Examples of Projects that Involve Expressive Construction

One large-scale example of providing youth with opportunities to develop computational literacies occurs in the Scratch ecosystem, which has been growing for more than a decade through a series of projects (NSF #0325828, #1002713, #1019396, #1027848, #1118682, #1348876, #1417663). Developed at MIT's Media Lab, Scratch is a block-based graphical programming language originally designed to help novices, including even young children, learn the basics of computer programming. Whereas traditional programming languages are arcane and difficult, the "low floor, high ceiling" design of Scratch has allowed users to write scripts that result in animations easily while also providing plenty of opportunity to progress to more complex computational ideas. Seeing, playing with, and working to improve these animations leads youth to develop their ability to "think computationally" — learning concepts such as sequences and loops and computer science skills such as modularizing and iterating.

Scratch is not just a language, but is also an ecosystem for participants to share what they have done and to learn from each other. As users gain experience with Scratch, the ecosystem provides opportunities to share what they have

Students examine a digital underwater environment and collaboratively create circuitry and lights to attract underwater creatures using *Oztoc* at the New York Hall of Science.

Used with permission of Matthew Berland.

built (and how they built it) with others. Further, to learn a new technique, participants can study examples that more advanced users have built. Sharing their work can help students develop computational practices such as remixing and debugging and perspectives such as connecting and expressing oneself through computational products (Brennan & Resnick, 2012).

The Scratch user base has grown over the years to become an international community of several million users. The Scratch developers at MIT's Media Lab have contributed research to the field, and the platform has also been used in numerous cyberlearning studies (see Resources). Indeed, Scratch has become an important platform for research sponsored both by the public and private sectors, both in the United States and overseas, and engaging researchers from many different disciplines.

The scale of Scratch use and research is an inspiration for many developers of programs that integrate play, making, construction, and expression. Within this scale, there is still much to discover about exactly which features, activities, and supports are most important to learning and which enable the broadest diversity of young people to grow.

Whereas Scratch emphasizes computational thinking, another cyberlearning project focuses on how students can learn about engineering with a lower threshold than taking an engineering course. In the **Makescape** project (NSF #1263814, #1263804) led by Leilah Lyons and Matthew Berland, researchers are investigating principles of play-based learning as visitors to the New York Hall of Science play a game-exhibit about engineering, *Oztoc*, on a digital tabletop. The museum draws a very diverse population, and most visitors to the exhibit are new to the engineering content of this game. To play, visitors must design electronic circuits that lure fish in groupings that reflect how biologists categorize fish. In support of collaboration, *Oztoc* gives

SiMSAM allows students to create stop-motion animations. They then crop objects from the animations to become 'sprites' that can be programmed with simple menu options.

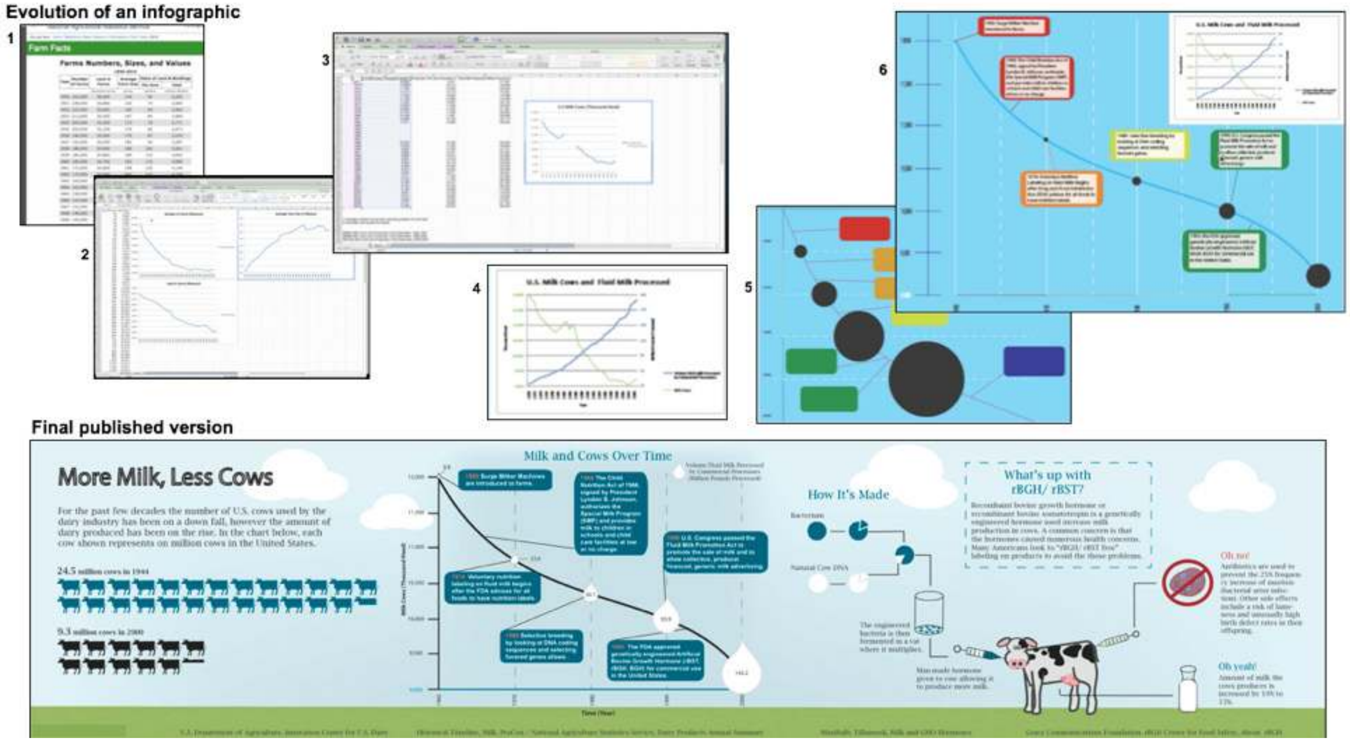
Used with permission of Michelle Wilkerson.

visitors an especially easy to use representation: physical blocks on a virtual tabletop. The blocks enable visitors to see each other's work and make their discussions richer. Research is finding that learning typically occurs when visitors explain to each other how to lure different categories of fish. Further, the researchers have found that a combination of physical blocks and screen-based representation is needed to lead visitors into deeper scientific and engineering practices. Research is demonstrating that while students at one level are simply playing with a game at a museum exhibit, at another level they are also learning to communicate about engineering ideas in ways that feel authentic and purposeful.

In other cyberlearning projects, researchers are finding that students can express scientific ideas through sketching and animation. For example, with Brian Gravel and Michelle Wilkerson's **Simulation, Measurement, and Stop-Action Moviemaking (SiMSAM)** (NSF #1217100), children make stop-motion animations and programmable simulations that use their own images and ideas to model invisible scientific phenomena. In a related project, Wilkerson and colleagues' **DataSketch** (NSF #1350282) technology enables young people to build data-driven visualizations by creating and programming their own sketches to illustrate patterns in data that have significance to them. Research in both projects has revealed that these tools enable students to show what they understand (and it can be much easier for students to express understanding with a tool than by responding to the traditional directive, "Explain your work"). Further, research indicates that the resulting sketches and animations help students to reason deeply about relationships and patterns that are important to the underlying science. The learning research in these projects demonstrates how connecting familiar self-generated representations (sketches and animations) to more formal technical representations results in active, engaged, effective learning of scientific concepts (Wilkerson-Jerde, Gravel, & Macrander, 2015).

Other expressive projects build on the mapping genre (discussed earlier) to connect familiar and formal ways of understanding. For example, Tapan Parikh and colleagues' **Local Ground** technology and initiative (NSF #1319849, #1646690) helps children use their familiarity with their neighborhood to explore broader scientific and environmental issues. With Local Ground, they create and modify data maps using a geographic information system (GIS) and geotagged annotations, photos, and measurements. Children have mapped soil quality in their local schoolyards in order to

Evolution of a STEM news infographic created by a high school student, from data selection, processing, analyzing, visualizing, and designing the final content and layout.



Used with permission of Joseph Polman.

understand the ecosystem they pass through every day (Lanouette, Van Wart, & Parikh, 2016). What links this project to the others in this genre is the strong focus on enabling students to express their emerging scientific ideas, in this case by making, marking up, and discussing their own maps. The innovative tools make it easy for students who are studying soil quality and biological organisms to add information to their maps — for example, by adding points, comments, and even photos. Further, the activities in which these tools are applied engage students in using their maps (and their friends' maps) to make scientific arguments about local environmental issues. Research has shown increased science learning when students use tools that allow them to express their own ideas using familiar, easy-to-use media (Lanouette et al., 2016).

The concept of computational media as enabling youth to develop a literacy is being developed in projects that are looking at journalism as a context for science learning. Researchers are finding that scientific argumentation grounded in data visualizations can arise in journalistic activities that invite youth to report on issues that affect their communities. For example, in the **STEM Literacy through Infographics** project, Joseph Polman and colleagues (NSF #1217052, collaborative awards #1441561, #1441471, #1441481) have developed a system in which high school youth take the role of citizen data journalists who publish a news magazine containing science infographics. To merit publication, the student journalists must tackle a rigorous editorial process and show their ability to communicate clearly to a public audience. Researchers identified the specific details of tools, resources, and social practices of feedback and revision that provide the collaborative support necessary for budding youth journalists. As the research helps us understand what tools youth need to refine their representations and their ideas, the activity of citizen science journalism has great potential for youth to develop agency as people who use STEM knowledge to help their community in meaningful ways (Gebre & Polman, 2016).

Other cyberlearning researchers are at the forefront of the maker movement, developing and investigating learning experiences that involve arts, crafts, and tinkering. Erica Halverson and Kimberly Sheridan (NSF #1216994) have found that makerspaces can help young people learn design practices that real-world inventors and engineers use, such as identifying problems, building models, testing prototypes, revising ideas, and sharing results with others. These researchers have learned how to arrange activities and resources to serve a range of ages and expertise in these spaces and have seen that multidisciplinarity fuels student engagement and innovation (Sheridan et al., 2014). More generally, researchers are also documenting how open-ended experiences let students develop agency, in contrast to fixed, kit-like experiences that too often focus only on getting something built and working (Konopasky & Sheridan, 2015).

Cyberlearning research is also pushing the frontier of maker tools and environments, aiming for low-cost or for more extensive functionality, in ways that tie to important STEM learning goals. Darrell Porcello, Sherry Hsi, Nikolaus Correll, and Michael Eisenberg (NSF #1451463) have developed "**paper mechatronics**": Makers design and craft foldable paper components and assemblies that help them learn the practices of mechanical engineering, electrical engineering, control systems, and computer programming. Benjamin Shapiro (NSF #1562040) and colleagues have developed a networked computer music toolkit called **BlockyTalky** (Shapiro, Kelly, Ahrens, & Fiebrink, 2016) that young people use to design and make instruments and input devices and to play music in groups. In the process of expressing themselves musically, the youth use complex computational practices such as pattern matching and utilizing messaging protocols over networks. In another example, Paulo Blikstein's **Fablearn** initiative has produced curricular resources, tools, and a growing community of educators concerned with the principled integration of fabrication and making into formal K-12 education (fablearn.org; NSF #1349163).

Contributions, Opportunities, and Challenges

The central ongoing research question in this work is how to interconnect appealing, playful environments that allow self-expression with activities that drive deeper learning goals. The dimension of time is important: How can play with computational objects result in learning at timescales of minutes or weeks or months or years? The dimension of context also needs more investigation: How do unique aspects of homes, museums, playgrounds, or classrooms contribute to or block learning? Strengthening our understanding of the social dimension is also critical as these activities often involve complex ecologies of support from peers, parents, and informal and formal educators, and they are not as simple as typical teacher-student interactions. Further, this research drives toward investigating how physical and digital technologies fit together in ways that can increase learning through making, gesturing, and talking. Overall, methodological challenges abound because learning in this genre often emerges from interactions among people, things, and computation in rich contexts and varied timescales.

Although this research can be challenging, the payoff is likely to be high as these projects connect to important societal themes. For example, the nature of work is changing to frequently involve groups of people working together with multiple technologies. Whereas a typical computer worker in the 20th century may have typed alone at a terminal, today workers use multiple computing devices collaboratively in settings that are rich with activities well beyond typing. Further, this genre's emphasis on rich modalities of interaction beyond typing — such as speech, touch, and gesture — connects learning experiences to broader societal experiences.

Thus, understanding how computational literacies support learning as youth collaborate in a complex activity will have implications beyond youth and STEM. For example, this work can lead to general innovations in user interface and user experience. Findings about new programming languages (like Scratch) could help in the design of programming interfaces for adult workers. Block-based, sketch-based, and other novel interface approaches may support accessibility and networked collaboration not just for learners, but also for a more general population. Most generally, we need greater insight into how people acquire new literacies, such as literacy with powerful representational tools. Major contributions of this work will be a better developed theory of how youth become fluent in expressing themselves in digital media, along with concrete examples, and evidence of their developmental trajectories towards rich ways of using computation to express their understanding of the world.

Finally, cyberlearning research in this area has the potential to inform education policy. Policymakers are considering how to invest in maker and other types of facilities for constructive activities, but are rightfully concerned about how to maximize learning and not just building things. This research is demonstrating how important learning can occur through playful, constructive experience, and it is also demonstrating what must be in place to ensure that learning occurs. When the right conditions are in place, what students are learning clearly relates to important STEM subject matter, such as engineering, and emerging subjects, like data science and computational thinking. Studying learning in playful and constructive settings can lead to new discoveries about when, where, and how children can learn important ideas, and these discoveries can guide policy about when, where, and how these important topics are taught.

Resources

CIRCL Primer: The Cutting Edge of Informal Learning: Makers, Mobile, and More!
http://circlcenter.org/the-cutting-edge-of-informal-learning/

CIRCL Primer: Computational Thinking: http://circlcenter.org/computational-thinking/

Scratch website: https://scratch.mit.edu/

Research papers and presentations on Scratch: https://scratch.mit.edu/info/research/

SiMSAM: http://sites.tufts.edu/simsam/

DataSketch: Making data-driven visualization accessible to middle school youth:
http://stemforall2016.videohall.com/presentations/6831

Local Ground: http://localground.org/

STEM literacy through infographics: http://science-infographics.org

INK-12: Expressive Digital Tools for Elementary Math Education:
http://resourcecenters2015.videohall.com/presentations/536

3. Classrooms as Digital Performance Spaces

By Tom Moher and Noel Enyedy

Design Description, Motivation, and Conjectures

Traditionally, the physical space of the classroom is arranged so that all students can listen to and engage with a teacher. The traditional classroom also lets students work individually or in small collaborative groups. Advances in technology such as tabletop displays have led to broad interest in more innovative uses of classroom space, but the interiors of classrooms remain largely devoted to keeping students in a fixed place – whether to listen to the teacher, to do individual work or to collaborate in a small group. What if classrooms could be reconfigured so that students were actively learning by moving around to engage with scientific phenomena? What if teachers and students could walk into the classroom and find them themselves immersed in an earthquake or a molecule? What if digital devices allowed the students to interact with the phenomena that appear all over the floors, walls, and furniture of the classroom?

- **Computer science innovation:** "Experience servers" that enable multiple people and devices to work together on a complex activity
- **Learning science innovation:** Reorganizing classroom spaces to facilitate movement and interaction in ways that enhance learning

Education research has demonstrated the importance of engaging both the minds and the bodies of students. Digital performance spaces provide immersive social and physical science experiences at the scale of the classroom, creating opportunities for students to learn about complex ideas in a collective and playful manner. These techniques allow educators to introduce important new scientific topics to students that are hard for students to experience in a traditional classroom format. Topics that are important to contemporary science but that are not in textbooks can now be learned.

For example, in **RoomQuake** (see below), the classroom occupies an imaginary area of intense seismic activity. Simulated seismographs in different locations of the room enable students to investigate the earthquake's effects and measure wave propagation and speed using tape

In RoomQuake, sixth-grade students move around the classroom to measure the distance to a simulated earthquake epicenter and to learn to interpret a seismograph.

Used with permission of Thomas Moher.

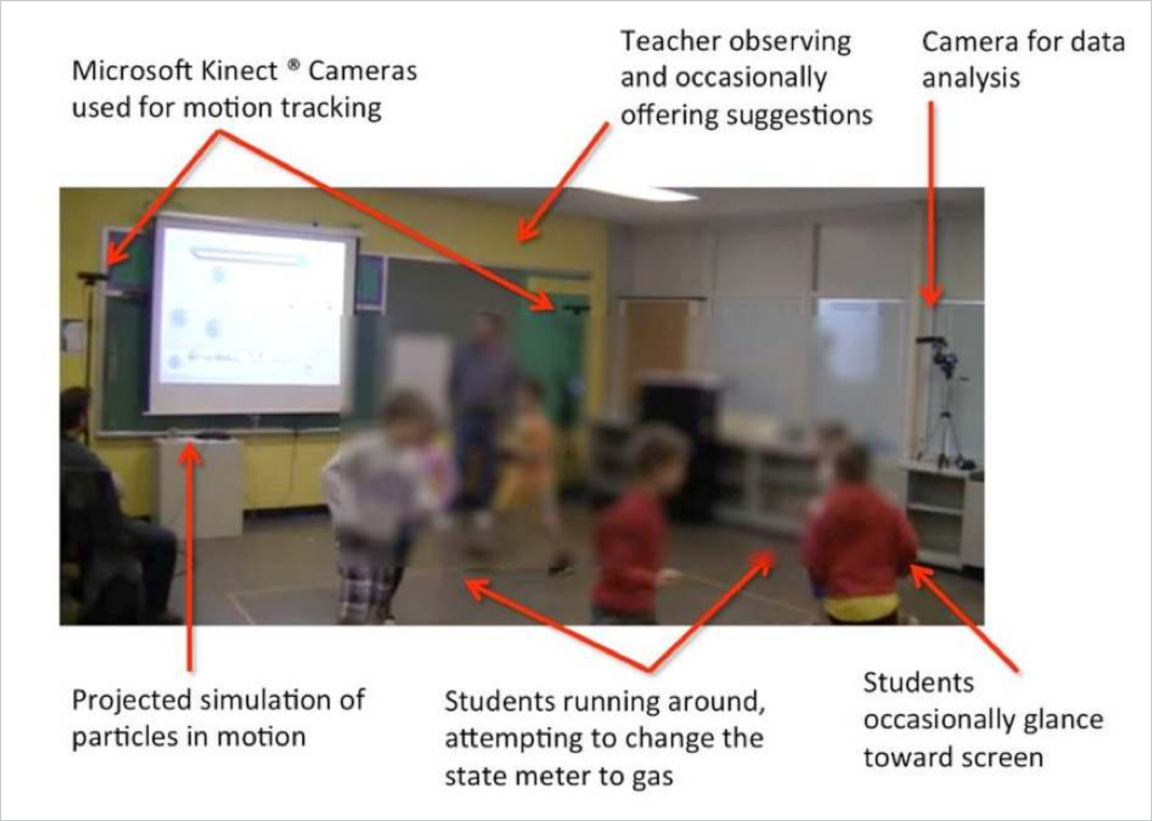
measures and stopwatches. As they investigate what is happening at each different place in the classroom, the students combine information to determine the time, distance, and strength of events from seismograms; locate "roomquake" epicenters; and witness the temporal, spatial, and energy distributions arising from a series of seismic events. Students have the social and scientific experience of doing fieldwork without ever leaving their classroom.

The promise of digital performance spaces builds on research findings about embodied cognition, which have demonstrated that that memory, mental metaphors, and concepts have roots in our physical actions and that we humans routinely assign meaning to the material world around us. A growing body of evidence links embodied interaction (Lindgren & Johnson-Glenberg, 2013) with positive cognitive outcomes, including improved memory (Wilson, 2002), understanding (Abrahamson, NSF #1321042), and spatial reasoning (Jaeger, Taylor, & Wiley, 2016). Research on digital performance spaces has also demonstrated positive impacts on the breadth, depth, and nature of student participation; on students' science-related attitudes; and on their ability to engage in scientific inquiry compared with similar content enacted outside the digital performance space (Moher et al., 2010). In addition, digital performance spaces are not only for short-term activities; Slotta et al. (2016) have shown how digital performance spaces can be used to support multiweek inquiry projects.

Examples of Classrooms as Digital Performance Spaces

Two kinds of digital performance spaces that have emerged through cyberlearning research are participatory simulations (Colella, 2000) and embedded phenomena (Moher, 2006). In participatory simulations, learners play roles in a digital simulation through their movement in a physical space. For example, in one classic participatory simulation, students explore how the spread of disease occurs more quickly or slowly depending on how people move and interact in a classroom. In the simulation, a few students can pretend to be initially infected and the disease spreads when their mobile device comes close to other students' mobile devices. A classroom of students can experiment with how rapidly disease spreads by orchestrating different patterns of motion of their own bodies. In this example as

Children playfully explore states of matter in the STEP classroom environment



Used with permission of Joshua Danish.

well as in all participatory simulations, individual actions (e.g., moving close to other students) lead to emergent collective phenomena (e.g., the spread of disease) that become the focus of classroom observation, conversation, reflection, and learning.

Thus, the spread of disease can be understood as system of interacting agents. It is very difficult to explain systems that involve many interacting agents to students through a lecture. In contrast, research has shown that participatory simulations have been successful in helping students learn about emergent phenomena in a complex system (DeLiema, Enyedy, & Danish, submitted).

In another participatory simulation project, Noel Enyedy, Carlos Wagmister, Jeffrey Burke, and Joshua Danish's **Science through Technology Enhanced Play (STEP**, NSF #1323767), motion-sensing cameras are used for continuous high-resolution tracking of elementary school students as they walk around and gesture within the physical space of the classroom. In a simulation of states of matter, students become water particles, and their physical motion and distance relative to each other dictate whether they collectively represent a solid, liquid, or gas. Large public displays show the result, and students use this visualization to make conjectures about the physical properties of solids, liquids, and gasses. They can then test the accuracy of these conjectures via collective experiments. The dual role of being both particles and scientists encourages a playful stance toward science that bleeds over into the formal activity of inquiry, where students can be wrong and even purposefully break the very rules that define the roles in the play situation. In a second activity, students enact roles as honeybees collecting nectar in virtual flower patches at the same time that they try to learn how bees communicate and organize themselves to collect enough nectar for the hive — and how they incidentally pollinate flowers during this activity.

Kylie Peppler, Armin Moczek, and Joshua Danish's **BeeSim** activity (NSF #1324047) offers another take on bee behavior, introducing digital sensors and stations to add new meaning to student movement. Students in a class enact the behaviors of a bee community as it tries to satisfy the energy needs of its hive. Positioned around the room are digital stations representing hives and nectar sources in the form of artificial flowers. Students form teams. Wearing gloves with sensors, they touch the artificial flowers to harvest nectar and return it to their hive. As they do so, their own energy use is monitored. If they use more energy than they collect, the bee community will die.

In the **Hunger Games** (NSF #1124495), Thomas Moher and colleagues used radio-frequency identification (RFID) tags to simulate the phenomena of foraging. The RFID tags are hidden in small plush animals that serve as avatars for student foragers. The foragers compete to have the most successful harvest while moving among habitats that vary in the amount of food and predators. During foraging, large public monitors in the classroom show how students' collective behavior results in more or less effective community use of available resources.

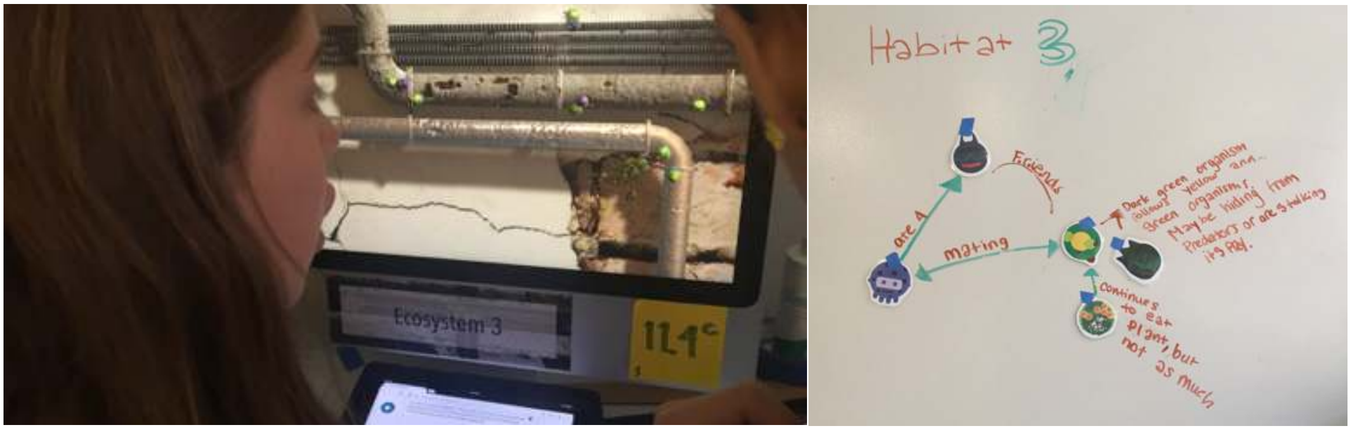
The other kind of digital performance space, *embedded phenomena,* is designed to give young learners an opportunity to engage in extended scientific inquiry, involving collective observation and manipulation of phenomena, collection of data, and construction of community knowledge over the course of multiweek projects. In an embedded phenomena activity, the object of inquiry is a shared simulated phenomenon, such as an earthquake, that occupies the space of the room. Computer screens are imagined as portals through which students can interact with the phenomenon. Because different components of the phenomenon are distributed around the classroom, students must work together to identify emergent trends and construct and use models of the phenomenon.

Child harvesting nectar in BeeSim

Used with permission of Joshua Danish.

Research has found that scientific learning occurs when students integrate observations and experimental results over multiple weeks to build models of the phenomenon and then use those models to make and test predictions and solve problems. In **WallCology**, for example, students observe and manipulate biotic and abiotic variables within ecosystems presented as animated habitats occupying the walls their classroom. The class collectively builds a population relationship web, which they then use as a tool for predicting the effects of invasive species and environmental change and for designing sustainable habitats. James Slotta and Thomas Moher (NSF #1065275) showed how these simulations could be integrated with community knowledge construction tools – and that doing so helps students to learn and engage in practices of scientific inquiry. In a complementary cyberlearning project, Thomas

Students observe and manipulate simulated habitats on the walls of their classroom to construct ecosystem models in WallCology.



Used with permission of Thomas Moher.

Moher, James Slotta, and Joel Brown (NSF #1324977) are extending techniques for building these simulations to enhance how students share their contributions with peers. This involves innovative computer science research on how to coordinate and display students' ideas across the physical space of the classroom.

Contributions, Opportunities, and Challenges

Collectively, these projects are advancing the learning sciences by introducing new activity structures for engaging in scientific inquiry that would not be possible without networked and mobile technologies. The resulting research is exploring novel strategies for sustaining interest, participation, and cognition as students tackle challenging science topics. This research builds on previous findings about feedback, visual representations, spatial mobility, and supports for collaborative learning (Roschelle & Pea, 2002). It examines how context shapes learning — and thus how deliberately engineering the classroom space can create powerful learning experiences. This new attention to using physical space as a learning resource is very different from an era in which simulations were either contained within a computer screen or in the "virtual space" of networked computer screens.

The computer science side of the research also relates to how technology supports social and experiential activities. The human-computer interaction (HCI) community has a long history of theory development based on the study of disciplinary communities, such as officers and sailors in the Navy working together as a collective using a variety of computer interfaces (Hutchins, 1995). The classroom is a demanding laboratory for testing new social and collective interfaces that enable people to do complex work together. For example, classrooms require highly reliable sensing and communication technologies in a densely packed space. The real-time demands of information coordination are high, and many dissimilar technologies must be integrated smoothly. All the projects described here include efforts to support management of complex devices and digital resources. They also are helping to create new form factors for collective interaction with room-size, spatially indexed virtual worlds and contexts for investigations of learners' multimodal interaction. This computer science work can have important implications for the design of collective interfaces for other contexts, such as teams in an aircraft control tower or a hospital floor.

The implications for K–12 education also deserve further investigation. For example, we anticipate a future in which we have the ability to track the locations of every child in a classroom along with hundreds of smart objects, in what might be called a **Classroom of Things.** BeeSim and Hunger Games demonstrate how simple discrete location tracking can be used for novel large-group STEM learning activities. This opens the door to new designs that use digital things as control tokens and access keys to open stores of information, as portable data and knowledge repositories, as badges of mastery, and as collectibles for young learners. New research in computer vision and radio and magnetic tracking technologies are advancing us toward this future. Cyberlearning classrooms are crucibles for developers of these technologies.

A challenge of this design centers on the demands on teachers to orchestrate technology-rich, room-size simulations. These activities require device installation, calibration, registration, and maintenance, which can pose significant barriers to adoption by teachers. Technologies that automate these operations (e.g., automatic calibration using embedded ultra-wideband meshes) hold great promise to lower those barriers. More tools are needed to enable participants to orchestrate the technology devices they have at hand, to manage the distribution of digital resources across those devices, and to recover from the inevitable failure of individual devices.

Despite the potential of this learning design, we do not expect that whole class performances are the right way to tackle all (or even most) STEM learning. Another important topic for education research is the *learning flow* across a set of very different types of technology-enhanced activities (Dillenbourg, 2002). Learning flow research looks at the blending of teacher and technology roles across multiple types of technology-rich activities. For example, we need to better understand the connections between classroom simulations and more conventional instruction. At the individual and small group levels, researchers have examined the relationship between gestures and the phenomena that they are intended to model. At the whole room level, new questions arise. Jaeger, Wiley, and Moher (2016) theorized that opportunities for perspective taking in a room-sized simulation (RoomQuake) accounted for differences in learners' performance on spatial reasoning tests. Recent work in the STEP project has introduced and tested theories of how particular blends of factors —embodied inquiry, peer discourse, classroom norms, and material and digital resources — can support learning (Enyedy, Danish, & DeLiema, 2015). Another theory suggests that immersive experiences contribute to participation and learning in part through persistent representation (Moher, 2006). These new theories need to be evaluated and elaborated on within the broader community, along with methodologies that address the challenges of capturing unmediated, widely distributed interaction among collaborating learners.

Resources

WallCology website: https://www.evl.uic.edu/moher/Tom_Moher/WallCology.html

Science through Technology Enhanced Play (STEP) video:
http://stemforall2016.videohall.com/presentations/726

BeeSim video: https://www.youtube.com/watch?v=KxjAAmNGJS4

RoomQuake website: https://www.evl.uic.edu/moher/Tom_Moher/RoomQuake.html

4. Virtual Peers and Coaches: Social and Cognitive Support for Learning


Virtual Peers and Coaches

By Judith Fusco, Wendy Martin, H. Chad Lane, and Catherine Chase

Design Description, Motivation, and Conjectures

Decades of research on expert teaching, human tutoring, and collaboration have established that the quality of a student's relationships with peers and teachers directly affects learning (Martin & Dowsen, 2009). Building on findings that show that people treat interactions with machines as a social experience (Reeves & Nass, 1996), cyberlearning researchers have investigated whether student learning could be supported through *pedagogical agents* (PAs). A PA can be an avatar that interacts with and helps teach learners. Unlike traditional computer-assisted learning systems, which simply provide feedback on user input, today's cyberlearning-based PAs draw on sophisticated artificial intelligence (AI) techniques and high-end animation systems to support both social and cognitive interactions. Whereas traditional systems used a mouse and keyboard for interactions, these new PAs often include speech, gesture, and other forms of input that are more like interacting with a person. These agents use verbal and nonverbal communication to establish a natural, welcoming learning environment. When implemented with appropriate pedagogies, such agents can increase learning (i.e., cognitive gains) while also improving motivation and student engagement (Schroeder, Adesope, & Gilbert, 2013; Schroeder & Adesope, 2014).

- **Computer science innovation:** Computational models for complex, realistic social and cognitive agents
- **Learning science innovation:** Virtual peers and coaches that provide affective, cognitive, and social supports for learning processes

Intelligent virtual agents build on almost three decades of learning research (Johnson & Lester, 2016). This large literature has identified a range of *roles* for PAs, including as virtual peers, teachers, or coaches; teachable agents (for reciprocal teaching); mentors; and adversaries (in competitive games). There is no single best way to use a PA. Research also has found that the technology can be used poorly, for example, increasing cognitive load (the amount

Virtual peer Alex recognizes and models verbal and nonverbal behaviors.

Used with permission of Justine Cassell.

of information a learner needs to keep track of). In a poor use, a PA may be an unwanted or unhelpful distraction. In this section, we highlight three recent successful examples of PAs in cyberlearning research that use AI innovations to put learning theories into practice.

Examples of Virtual Peers and Coaches

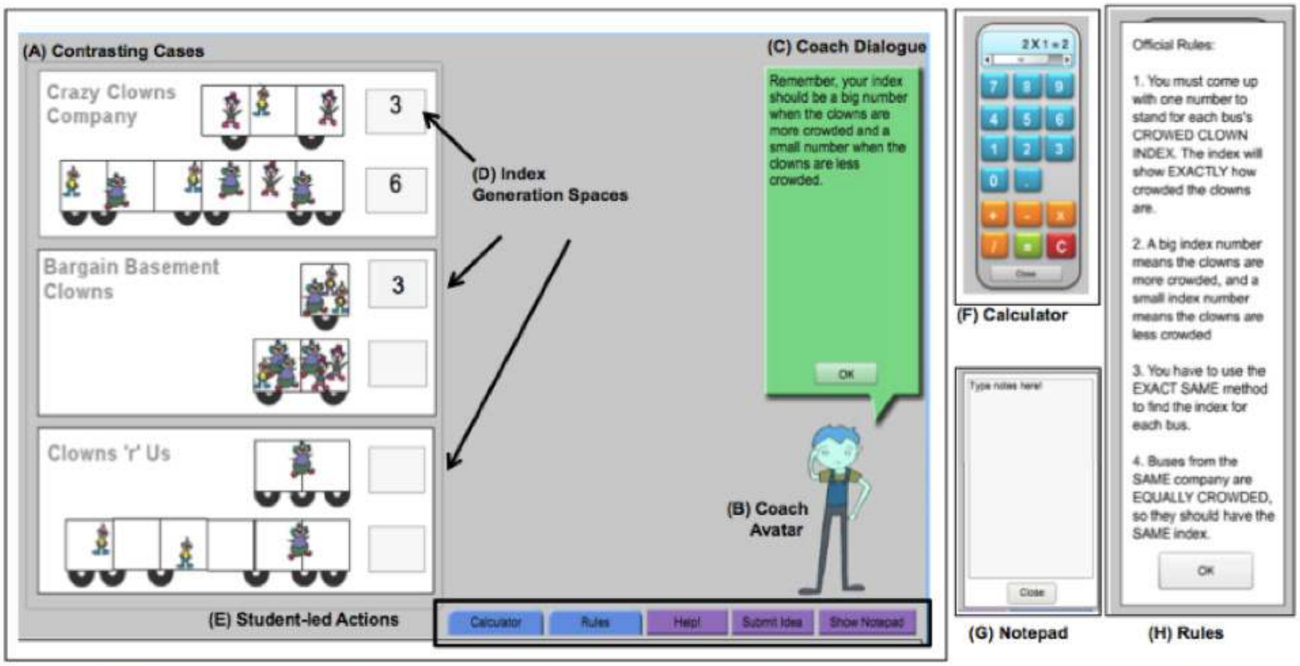
The lab led by Justine Cassell at Carnegie Mellon University has developed a virtual peer named **Alex** (NSF #1523162), who is designed to be gender ambiguous. Alex collaborates with learners as they explain scientific concepts. Using models of effective social collaboration built on the basis of analysis of extensive peer-peer conversations, Alex can converse with a child in a normal manner. Alex's behavior can be adjusted to explore the effect of different interactions on learning, such as variation between standard language and dialect. This technology also has been used to help children with autism, to integrate storytelling and learning, and to develop science reasoning and science discourse.

In an NSF Cyberlearning-funded project, Cassell's team is investigating how a virtual peer can build rapport with a human learner and what the effect of rapport is on learning. Rapport, which is informally understood as one's ability to have fluid, natural, and harmonious interactions with another person, is achieved computationally by building models that sense and attend to emotional and social cues during conversation (Zhao, Papangelis, & Cassell, 2014) and respond in kind. Building rapport is technically demanding, requiring multimodal sensing, which builds on recent advances in computer vision, signal processing, and machine learning, and multimodal generation of appropriate social strategies, which builds on new techniques in machine learning. In this project, the virtual peer automatically recognizes audio and visual behaviors during learner interactions and employs a decision module to select from appropriate social and task moves during the dialogue (initial work reported in Madaio, Ogan, & Cassell, 2016).

The team also developed abilities for the virtual peer to communicate in multiple dialects and to switch among the dialects within a conversation with a student, depending on the context. In one project (funded by the Heinz Foundation), the virtual peer has been used to test hypotheses about how to best support students in learning to speak in appropriate “school English” when needed. For this work, Alex was augmented with an ability to speak in African American Vernacular English in addition to standard English or even to rapidly change (“codeswitch”) among the dialects at different times in their dialogue. Research with the virtual peer has demonstrated that using a familiar dialect builds rapport and that rapport mediates the relationship between dialect and learning. Learners exhibited greater scientific reasoning in their contributions when they were able to speak in their own dialect (Finkelstein, Yarzebinski, Vaughn, Ogan, & Cassell, 2013). The research findings have broad implications, both for technology design and policy. They are relevant to practices in schools, for example, in determining whether teachers should require students to use only standard English or to support dialect switching.

Another cyberlearning project involving a pedagogical agent is the **Invention Coach** (NSF #1361062) developed by Catherine Chase and Vincent Aleven. This virtual coach supports students through invention tasks; research has shown that invention tasks prepare students to learn in the future (Schwartz & Martin, 2004). The system provides students with feedback to promote exploration. After the exploration phase,

The Invention Coach’s main interface where a student works to invent an index of “clown crowdedness,” a proxy for density (mass/volume).



Remember, your index should be a big number when the clowns are more crowded and a small number when the clowns are less crowded.

Official Rules:

1. You must come up with one number to stand for each bus's CROWED CLOWN INDEX. The index will show EXACTLY how crowded the clowns are.

2. A big index number means the clowns are more crowded, and a small index number means the clowns are less crowded

3. You have to use the EXACT SAME method to find the index for each bus.

4. Buses from the SAME company are EQUALLY CROWDED, so they should have the SAME index.

Invention Coach Main Interface. The goal of the task is to invent an index of “clown crowdedness” for each of the buses in the contrasting cases (A). Students receive support from the Coach (B) in the dialogue box (C), and input their ideas into index generation spaces (D). Additional student-led actions (E) include accessing the calculator (F), taking notes in the notepad (G), reviewing the rules (H), or soliciting help from the coach by clicking “Help!” or “Submit Idea.”

Used with permission of Catherine Chase.

the coach seeks to maximize the value of direct instruction (Marks, Bernett, & Chase, 2016). Because open exploration and discovery can be overwhelming for some learners, the Invention Coach system was designed to guide students through this often messy and iterative process.

The Invention Coach goes beyond traditional intelligent tutoring systems by supporting learners as they tackle *ill-defined* problems (Lynch, Ashley, Aleven, & Pinkwart, 2006), such as the process of invention. To address this challenge, an interdisciplinary team investigated what kind of guidance effective human coaches use to promote transfer from one learning task to another. They found that effective one-on-one human invention coaches asked questions and did not give answers, which is compatible with most studies of expert human tutoring in general. Further, the *more* explanations a coach gave, the lower the transfer test score for the student. These findings inspired the research team to develop an adaptive Invention Coach that avoids giving direct feedback or didactic explanations. Instead, the coach provides a balance of problematizing and structuring feedback, which encourages learners to diagnose their own errors. A classroom study of the Invention Coach found that it led to greater transfer than no guidance and minimal guidance versions of the system.

A third example is research led by Kristy Boyer, Brad Mott, James Lester, and Eric Wiebe (NSF #1721160, #1640141, #1409639, #1138497). In working with educators, the researchers were inspired by the challenges of trying to design an educational game that appeals to girls. Together, they found a solution in using a virtual agent in the role of a learning companion. The companion, **Adriana**, takes the role of a younger peer. Adriana's backstory was that she was "the little sister" of a character in the game. Players consult with Adriana about how to succeed in the game world. As they converse with her, they simultaneously learn and gain an empathetic ally. The researchers found that by talking with Adriana, girls overcame initial frustration that had previously been seen to lead to a gender gap in gameplay outcomes. These results along with previous research suggest virtual agents may help in other areas and with a wide range of skills.

Adriana, the learning companion.


Hey, what's your name?

Used with permission of Kristy Boyer.

Contributions, Opportunities and Challenges

Cyberlearning research on PAs is pushing the frontiers of human-computer interaction and AI-based agents, as well opening new doors for learning sciences research. For example, research on virtual agents can give us a better understanding of the interplay between affect and cognition and lead to better support for learners. Improved scientific understanding of how to create empathetic virtual agents not only can improve learning outcomes in specific cases, but also has potential to help address equity issues in STEM learning. Further, designing computer agents that can establish rapport with a student will most likely be important for advancing human-computer interaction in general.

Investigating PAs also highlights important and difficult research challenges. An obvious challenge is the difficulty of translating what we know about human social and cognitive support into virtual systems — and also identifying what parts of the learning experience are best left to human educators and peers. Understanding the limitations as well as the strengths of PAs will improve the design of learning environments that combine the best of computer-based and human coaching.

Specific research questions can also be fruitfully explored with PAs as research tools. For example, the role of gender in mentoring interactions can be systematically explored by varying the gender of the agent. Likewise, personality factors can be systematically varied and effects on learning can be investigated. The value of storytelling as a component of how students learn science concepts can be investigated while also exploring how stories and social interaction may help improve attitudes toward STEM.

The technical dimensions of this research demand advances in methods. Cyberlearning researchers engaged in PA research are using multimodal data analysis (combining forms of data such as eye-tracking, gesture recognition, and speech recognition) to better monitor and integrate the emotional responses a learner shows. Further, modeling these data to improve tutor dialogue is driving new applications of research from natural language processing. As these approaches mature, PAs can integrate with the other genres discussed in this report to augment the human support available to learners to engage deeply and effectively.

Resources

CIRCL Primer: AI Applications in Education: http://circlcenter.org/ai-applications-education/

5. Remote Scientific Labs: Authenticity at Distance

Remote
Scientific Labs

By Jeremy Roschelle, Kemi Jona, Patricia Schank, Shuchi Grover, and Wendy Martin

Design Description, Motivation, and Conjectures

Cyberlearning researchers are redefining what a laboratory experience can be for teachers and students. Labs are widely considered to be essential to learning science and engineering because they engage students in hands-on inquiry using tools and procedures similar to those of real scientists and engineers (National Research Council, 2006). However, it is not always possible to provide students with high-quality school-based laboratory experiences. Labs can be expensive, dangerous, difficult, and time consuming (Chinn & Malhotra, 2002). A remote laboratory enables educators and students to conduct scientific experiments over the Internet (Ma & Nickerson, 2006). Remote lab users can access sophisticated scientific apparatus, often at low cost, with greater safety and more convenience than school-based labs. Students often struggle with the procedures in school labs, but because remote labs are controlled by a computer, procedures can be precisely executed (Chinn & Malhotra, 2002). This can allow time for students to replicate or extend experiments, making it simple to vary conditions and efficient to run multiple experiments.

- **Computer science innovation:** Interfaces that increase realistic presence as people engage in complex tasks in remote settings
- **Learning science innovation:** Understanding how to make authentic scientific experiences available to many more learners and what aspects of authenticity are most important to learning

Remote labs have been used in education for a number of years and have already had an impact on science education globally, making them an established learning genre. Recent cyberlearning research is pushing the boundaries of the genre, however, by drawing on the latest technological advances that enable learners to interact with data, tools, and scientists in new ways. As researchers are making use of such technologies as cloud-based and mobile computing and cameras and data visualization tools in remote labs, they are gaining important new insights into how people learn.

More than 11,000 users worldwide have run more than 16,000 experiments on ilabstudio.org.

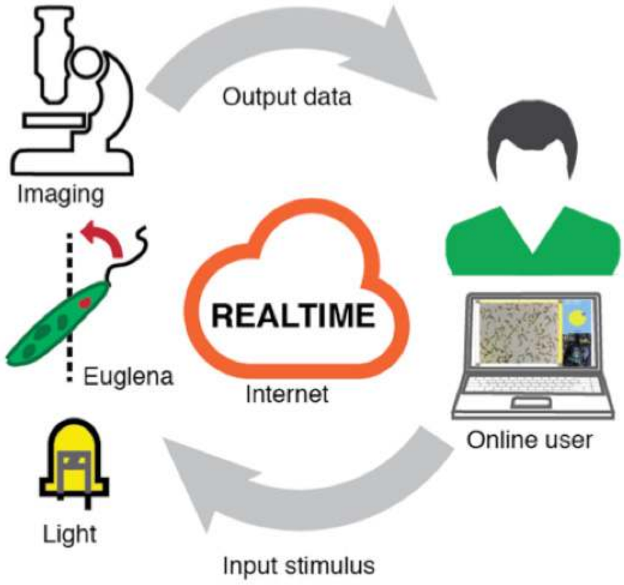
Used with permission of Kemi Jona.

Examples of Remote Labs

One exemplary remote lab advances learning of microbiology. Ingmar Riedel-Kruse and Paulo Blikstein designed this lab as part of their cyberlearning project Taking Hands-on **Experimentation to the Cloud: Comparing Physical and Virtual Models in Biology on a Massive Scale** (NSF #1324753). This project addresses the difficulty of doing experiments with biological organisms in school. Using a technique called Bifocal Modeling, the lab combines biological experimen Examples of projects using learning analytics for assessment ts with simulation models in real time – increasing learning by moving the focus back and forth between live and simulation views. Research in the learning sciences has established that science learning should connect tools for modeling with tools for gathering data. Before this project, it was unclear how to make these connections in a remote lab setting. This project's researchers designed an online platform where students can remotely observe *Euglena* cells swimming in a small dish. The students can shine light on the small organisms using a virtual joystick control, and when the light hits the cells, they can see how the organisms swim away, in real time. Two cameras are used: one for a microscope so students can see the cells, and another to see the light source. After making observations, students program a simulation to reproduce the phenomenon. Students learn how to make sense of *Euglena's* behaviors by trying to match scientific theories to the real world.

A project led by Kemi Jona of Northwestern University is also pushing the boundaries of teaching and learning through remote labs. His research with radioactivity labs showed that students prefer the remote lab to a simulation. Although it might seem that a local experiment would seem more "authentic," his research found that the video presence with real scientific apparatus supports their experience of the remote lab as authentic, and that the video helps them

A real-time interactive biology platform allows users to send light stimuli to biological substrates, such as phototaxic *Euglena* cells, and observe the response in real time (Hossain et al., 2016)**.**



Used with permission of Ingmar Riedel-Kruse.

Student using iLabs.

Used with permission of Kemi Jona.

understand radiation by allowing them to vary their measurements. Through his more recent work on the **Transforming High School Science via Remote Online Labs Cyberlearning** project (NSF #1216389) and other similar projects, Jona has led the development of a new user platform, **iLabStudio** (ilabstudio.org), that improves educators' and students' remote lab experience. For example, remote labs have traditionally been available only on desktop or laptop computers. His recent video, *Remote Labs: A Lab in Every Pocket,* shows how to gracefully extend the experience to mobile equipment. The features included in the new user platform, developed through an iterative design process involving both teachers and students, led to new insights into how to support high-quality interaction and learning with a lab in a mobile setting. Since more high school students have access to mobile than to desktop computing, this work could lead to scaling up access to authentic scientific lab experiences.

In another project, **Using Dynamic Formative Assessment Models to Enhance Learning of the Experimental Process in Biology** (SimBio, NSF #1227245), Eli Meir is enhancing how labs can measure students' learning and provide them with immediate feedback as they experiment and reason about lab results. The project is based on prior research showing, for example, that providing students with visual models of otherwise invisible processes such as diffusion and osmosis can overcome their misconceptions (Meir, Perry, Stal, Maruca, & Klopfer, 2005). It is challenging to provide appropriate feedback with virtual labs because they allow students to explore and discover concepts on their own.

This project seeks to understand the sweet spot where learners have the freedom to explore, try things out, and refine ideas. Engineering the sweet spot also requires designing enough constraint to enable computational algorithms to interpret what learners are doing and provide them with feedback and assistance. Hence, research on remote labs is also leading to better design of environments that support an active, constructive learning process and facilitate deeper student learning.

Contributions, Opportunities, and Challenges

Cyberlearning research in the remote lab learning genre is creating opportunities for learning scientists and computer scientists to work together to broaden participation in science by increasing the availability of authentic scientific equipment to many more students in many more locations. Remote labs open up possibilities to extend accessibility of complex scientific gear to investigators with disabilities and those in rural settings. With remote labs, designers can also customize the user interface of a physical lab instrument to the needs of the learner and the intended learning outcomes. This is impossible in working with physical equipment that is often designed for professional lab technicians or doctoral-level researchers.

Some labs that primarily investigate physical phenomena, but there are also are remote labs for computational environments. Using these labs, computer scientists are testing designs that to create high-performance computing environments that are accessible to diverse learners everywhere, not just learners who live nearby to a high-performance computing facility. For example, the objective of the NSF-funded **Extreme Science and Engineering Discovery Environment** project (XSEDE) (NSF #1053575) is to prepare the current and next generation of researchers, educators, and technology innovators to engage in a unified virtual supercomputing collaboration and data sharing environment. Goals include not only eliminating distance as a barrier, but also improving user interfaces so that a greater diversity of people can engage meaningfully with high-performance computing facilities.

The learning science advances address how to better support authentic scientific inquiry, provide formative assessment, and enhance collaborative learning in remote lab environments. For example, scientific inquiry does not happen merely because authentic scientific instruments and experiments are available. Because remote labs can engage thousands of learners in the "same" experience, they are perfect settings for varying the support for learning and investigating what supports accelerate learning (see, for example, Nickerson, Corter, Esche, & Chassapis, 2007). Further, formative assessment becomes an important challenge because users need feedback to maximize their learning from labs. How can one user benefit from what his or her peers are doing in the same (or a different) remote lab? How can remote labs support learning communities in scientific investigations? Remote labs also allow researchers to study the benefits of managing students' focus among the many different aspects of conducting an investigation, so that students are not distracted by incoming data when they should be thinking about their experiemental design, for example. Most school labs require students to spend the majority of their time on equipment setup/cleanup and collecting and logging data, with little or no time for designing novel experimental parameters or running multiple trials. Remote labs can decrease the amount of time students need to spend on the logistics of doing an experiment, and can increase their attention to conceptual learning.

Key computer science challenges concern expanding the sense of presence. Surprisingly, a remote lab can feel more real to students than a local experience with simplified or less authentic equipment. However, much work is still needed to expand users' sense of presence to include social participation — students today have less sense of being in the same remote lab together. Another challenge is how to scale the sense of presence smoothly across a range of bandwidth and local computing resources, for example, from learners in more remote, rural locations to learners who may access a remote lab on a phone and may have the ability to view the lab across multiple displays. A related issue is being able to interact with lab equipment that requires a real-time connection as opposed to asynchronous interactions. The knowledge gained from resolving such challenges with remote labs can lead computer scientists to develop techniques to make other forms of collaborative remote work more effective.

Resources

CIRCL Primer: Remote Labs: http://circlcenter.org/remote-labs/

Video: Remote Labs: A Remote Lab in Every Pocket:
http://resourcecenters2015.videohall.com/presentations/497

iLabStudio: http://ilabstudio.org/

Bifocal modeling: https://tltl.stanford.edu/project/bifocal-modeling

Extreme Science and Engineering Discovery Environment (XSEDE):
http://www.ncsa.illinois.edu/enabling/xsede

6. Enhancing Collaboration and Learning Through Touch Screen Interfaces

By H. Chad Lane and Emma Mercier

Design Description, Motivation, and Conjectures

With the introduction of touch screens to devices such as phones and with the development of iPads and other tablets, the nature of interaction with computers has changed. No longer are people limited to solely interacting with a computer through a single point of contact, such as a mouse provides. Now we are able to touch the screen with multiple fingers and use gestures to move, resize, and rotate objects with greater naturalness and ease. Because it is substantially easier to use these touch interfaces than the earlier mouse and keyboard interfaces, even young children are able to control complex interactions (Nacher, Jaen, Navarro, Catala, & González, 2015). In addition, multi-touch allows more than one user to touch the screen at a time, and groups can collaborate on a single device more fluidly.

Increasingly, touch screen technologies such as tablet computers are being adopted in classrooms – however most are being used in the same ways that laptop computers were used. Hence, in conventional use the only advantage of a touchscreen computer is that it is less expense. In contrast, Cyberlearning researchers are investigating how the unique types of interaction possible only on a multi-touch device can make it easier to learn challenging intellectual content and for collaborative learning. Early findings are encouraging. Research indicates that groups engage in more task-focused and less process-focused conversations using multi-touch screens compared to single-touch screens (Harris et al., 2009). Multi-touch tabletops, compared with paper, are associated with more conversations that build on the ideas of others in the group (Mercier, Vourloumi, & Higgins, 2015). Compared with groups working on traditional computers, use of a touchscreen for group learning is associated with more joint activity (Basheri, Burd, & Baghaei, 2012). In addition, research has shown that

- **Computer science innovation:** Expanding collaboration via tabletop computers, mobile devices, and sketch interfaces
- **Learning science innovation:** Pedagogical designs for collaborative learning and for supporting effective teaching

students can use multi-touch tabletops to create shared diagrams to support their collaborative problem-solving activities, such as sketching a circle to connect clues when solving a logic reasoning task or organizing information spatially so a group of students can easily keep track of reasoning tasks that are decided or still under consideration (Mercier & Higgins, 2014).

Examples of Learning Via Touch

An example that brings these ideas together is the **Collaborative Support Tools for Engineering Problem Solving (C-STEPS)** project (NSF #1628976), led by Emma Mercier and colleagues at the University of Illinois, Urbana-Champaign (UIUC). C-STEPS is motivated by the real-world challenge of providing engineers with opportunities to develop 21st century skills, such as collaboration, communication, and applying shared knowledge. As they begin their training, engineering students often find themselves listening to lectures and working on abstract problem sets individually, with few opportunities to engage in authentic collaborative problem-solving activities more typical in the engineering profession. C-STEPS builds on efforts at UIUC's College of Engineering to address this problem by engaging students in collaborative work early in their program. Students work either on shared multi-touch tables, which provide a single workspace for the co-construction of solutions, or on software that allows for the syncing of groups of tablets, creating a single workspace that spans multiple small tablets. Working with the engineering faculty, Mercier's team has designed a framework for developing authentic collaborative tasks in which students must make design decisions as a group (such as where to place books on a bookshelf) and then conduct calculations to justify their choices (such as determining the bending moment and the amount of force applied by the books on the shelf to determine whether the shelf will hold the books in the position selected). Mercier's research has shown that this kind of tabletop-mediated collaboration is superior to nontechnological counterparts (e.g., Higgins, Mercier, Burd, & Joyce-Gibbons, 2011) because it requires and supports the creation of shared project work by the learners in a group. Students both learn key collaborations skills and learn more cognitive content when they must present and defend their ideas.

Using C-STEPS tools, students sketch designs and co-construct engineering solutions.

Used with permission of Emma Mercier.

C-STEPS research also addresses educators' needs. Instructors and teaching assistants are able to monitor the work of individuals and groups on their own tablets. Further, instructors can share work between individuals, small groups, or entire class. This can enhance class discussions and enable groups to learn from the different ways others solved the problem. Mercier's current research not only builds on these important initial findings; it also seeks to integrate novel data mining techniques to identify struggling individuals or groups automatically. When a student or group is struggling, C-STEP can alert instructors to difficulties and provide them with insight into how to intervene. To validate the data mining alerts, the researchers are currently comparing log files from the tablets to videos of students' interactions. The relationships between the log file data and video observations will be used to create representations for the teaching assistants, providing them with insights into the groups' processes and prompts for how to intervene and support the students as they begin to develop collaboration skills.

As in their earlier discussion of expressive representations, sketching solutions is critical in C-STEPS because it allows learners to express their ideas and to share representations with their groups. Sketching and touch-based interfaces have a key role in many more cyberlearning-related projects as well. For example, the **Technology for Mathematical Argumentation (TMA)** project (NSF #1019841, #1020152) enables young students to explore algebraic reasoning before learning about formal algebraic proofs. Through sketching and interaction with visual representations, they are able to explore these complex ideas and share them with the class. Another example is **Touch Counts**, an interactive tablet-based environment that allows young learners to explore enumeration, sequence, operators, and more via multi-touch gestures. Finally, the **PerSketchTivity** (NSF #1441291, #1441331) project at Texas A&M seeks to provide automated support for recognizing and assessing undergraduate engineering design tasks. The system provides feedback on designs, and researchers are investigating to what extent the support promotes better sketching skills, understanding, and communication.

Contributions, Challenges, and Opportunities

This work contributes to computer-supported collaborative learning, exploring how new interaction tools can be used to support students as they learn with others. The challenges in implementing these tools, particularly in classroom settings, are engaging computer scientists in issues related to data analytics and representations and exploring how teachers can use log file data during classroom activities to provide appropriate guidance to individuals and groups. For example, recent education research suggests that the task demands and group size need to be taken into account when determining the size of screens that groups should use (Shehab & Mercier, 2017), which has implications for a broad range of design problems and disciplines.

The potential of using data mining and analytics to understand what students are doing when they work with touch screens both individually and in teams poses challenges for future research. Understanding the relationship between actions on the screens and learning behaviors as observed (e.g. on video) will provide new ways for students to monitor their own learning or for teachers to determine when and how to intervene, when to move students to more complex tasks, and when to return to review specific concepts. The potential for gaining insight into the relative black box of collaborative learning in multiple groups within classrooms will add to our understanding of collaborative learning, providing us with insights into how to prepare future teachers to use collaborative learning tasks in their classrooms, with or without technology.

Overall, multi-touch interfaces are affordable, popular and easy to use. Cyberlearning researchers going beyond the obvious uses of this ubiquitous technology to find ways to strengthen collaborative learning.

Resources

C-STEPS project: http://www.colearnlab.org/csteps

Technology for Mathematical Argumentation Project: http://tma.mit.edu

Touch Counts: http://touchcounts.ca/

SketchTivity: http://sketchtivity.com

CSTEPS: Collaborative Sketch Tools for Engineering Problem Solving:
http://resourcecenters2015.videohall.com/presentations/515

Illustrative Cyberlearning Methods

> *Cyberlearning brings together an interdisciplinary group of researchers that can critically consider how to plan for the future of learning. Specifically, by sharing research about new genres that are being developed, researchers are able to broaden their own perspectives on the future of learning.*
>
> —Marcelo Worsley, Northwestern University

As discussed in the designs above, new genres of learning technology drive new research questions and call for new ways to investigate learning. This section features three methods that cyberlearning researchers are developing to investigate learning with emerging technologies.

1. Multimodal Analysis

By Marcelo Worsley

Multimodal
Analysis

Method Description, Motivation, and Conjectures

Cyberlearning researchers are using innovative methods to investigate how people interact with learning designs and to measure their impact. Learning scientists rely on multimodal analysis — analysis of visual, audio, gestural, movement, and other data sources — to draw inferences about what and how students are learning. For example, using videos, researchers have looked at facial expressions, gestures, tone of voice, and discourse to understand how people learn (e.g., Barron, Pea, & Engle, 2013; Koschmann, Stahl, & Zemel, 2007). Historically, video analysis has provided a means to get a rich picture into complex human-to-human and human-to-technology interactions in learning environments. However, video analysis has often been painstakingly slow, and video does not capture everything that happens in a learning environment. New data streams (such as clickstream log data from playing a game, movement data from sensors, audio data from microphones, and visual data from cameras) and new computational tools for analysis are now transforming how researchers measure and evaluate the impact of cyberlearning projects on learners.

- **Computer science innovation:** Combining multiple forms of data and applying machine learning algorithms and probabilistic models to make sense of how people interact with technology
- **Learning science innovation:** Using the streams of data from different devices to find new patterns in how people learn in complex environments

Using these new data streams is important because the data can enable researchers to ask and answer new questions about learning. Sensors can measure stress or arousal, facial expression, eye gaze, heart rate, and many other things beyond what can otherwise be observed on a video. One example of such a sensor is electrodermal activation, commonly referred to as skin conductance. This sensor detects the increased perspiration that the body exhibits when a person is stressed, surprised, or under significant cognitive load.

This increase in perspiration is frequently hard to perceive for observers except in instances of extreme nervousness or arousal, and it is virtually impossible to quantify through human observation. Measuring this affective response along with indicators of cognitive activity can help researchers to understand how affect and cognition are related while students learning. Important new questions that can be asked and answered include: When a student learns about physics or another topic in an augmented reality experience, is some amount of tension (or stress) good? How much tension is too much? When students are stressed, how does what they look at in a learning environment change?

Examples of Projects Using Multimodal Analysis

In one of many cyberlearning projects that analyze multimodal data, James Lester is studying the relationship between student emotions (affect) and student learning. The project, **Adapting to Affect in Multimodal Dialogue-Rich Interaction with Middle School Students** (NSF #1409639) gathers data on facial expression, posture, gaze, speech, heart rate, skin conductance, and actions. Research involves developing a model of changing affect as students participate in the **Crystal Island** virtual environment, where students play the role of a medical field detective investigating a mysterious infectious disease outbreak. The multimodal information will help researchers capture each learner's experience and also understand elements of the environment

Crystal Island, a game-based learning environment for middle grade science and literacy, raises challenging issues of how emotional responses — such as feelings of calm or tension — are involved in learning.

Used with permission of James Lester.

that may elicit unexpected or surprising responses from learners. Furthermore, the analysis is helping the researchers improve the environment to better integration emotions and learning.

Other researchers are using multimodal analysis to study collaborative learning experiences that do not involve computers. Schneider and colleagues (2015, 2016) used mobile eye trackers to study students as they collaborated with 2-D and 3-D objects. The mobile eye trackers and video recordings allowed them to examine when learners were paying attention to each other and to the objects. They found this approach could accurately predict student performance and learning gains. Worsley, Scherer, Morency, and Blikstein (2015) used multimodal data to study collaborative learning in an engineering design context. Students worked with everyday materials to complete a design challenge. The researchers had hand/wrist movement, electrodermal activation and speech, head pose, and facial expression data. To analyze this data, they developed an automated process to break the stream of data into meaningful segments and then analyze learning with the segments. Ultimately, they found that the automated method outperformed traditional methods from education research and from computer science. The automated approach resulted in better models of the quality of students' engineering designs and how much they learned compared with more traditional approaches that relied on people to make observations and perform analyses.

Finally, a number of researchers are examining opportunities to use multimodal analysis to investigate embodied learning. In the **ELASTIC3S** (NSF #1441563) and **Developing Crosscutting Concepts in STEM with**

ELASTIC3S explores ways that body movement can be used to enhance learning of big ideas in science.

Used with permission of Robb Lindgren.

Simulation and Embodied Learning (NSF #1441563) projects, Robb Lindgren is using multimodal sensors to study how embodied learning can support students as they learn STEM concepts: How do students use gestures in learning science? Dor Abrahamson in **Collaborative Research: Gesture Enhancement of Virtual Agent Mathematics Tutors** (NSF #1321042) is developing a gesture-based virtual agent to support students as they learn about fractions. The virtual agent (see also the Virtual Peers and Coaches section) is being developed by analyzing teachers' and learners' gestures. The gestures being investigated go beyond simple hand movements by incorporating facial expression and posture. Going back to early scholars like George Herbert Mead (who died in 1931), social scientists have known that gesture is important to the process of learning. New multimodal analysis methods are now enabling scientists to analyze more data, more systematically to understand exactly how gesture plays into learning.

Contributions, Opportunities, and Challenges

Multimodal analysis is likely to advance both the learning sciences and computational sciences. In the learning sciences, reliable low-cost sensors enable deeper investigation of how people learn in complex environments. When coupled with machine learning, multimodal analysis can give researchers novel insights into the efficacy of a given intervention or the emergence of different patterns in their data. In computer science, researchers are developing algorithms, models, and visualization techniques that push the boundaries on how analysts engage with data. There is important work to do to achieve an analysis workflow that is sound, efficient, and integrates human insight with computational power.

Key challenges to conducting this kind of research (Blikstein & Worsley, 2016; Worsley, 2012) span every step of the workflow from data collection (collecting reliable synchronized data from several data streams) to data analysis (determining the appropriate tools and analytic techniques for processing and integrating the streams). Although the vision of using big data can make it seem easy to gain insights rapidly, the reality is that working with these new data sources and analysis techniques remains very challenging. To address these challenges, the **Catalyzing Research in Multimodal Learning Analytics** project (NSF #1548254) has been organizing workshops that introduce participants to some of the capabilities of multimodal analysis and provide them with preliminary resources for using the techniques. Additionally, the principal investigator of this project, Marcelo Worsley, is developing the **Multimodal Data Capture and Analysis Tool,** which will significantly streamline the process for collecting high-quality data and employing that data as evidence for learning.

The workshops have identified three key directions for research:

1. Making it easier or faster to incorporate new or additional data streams into existing research approaches.
2. Identifying new research questions that can be asked and answered only with new data streams.
3. Using multimodal tools to develop new learning experiences and new ways of engaging with learning data.

Many of the new research questions relate to learners' socio-emotional experiences — and the new streams are important because they can more directly collect information about emotional responses and the changes in gaze, gesture, and posture that show how people are relating socially. Society has already started to see the learning possibilities that emerge when a speech-activated device is added to a home or school. Multimodal tools can lead to learning experiences that adapt more fully to various learners' abilities, emotions, needs, and preferences.

Resources

Crystal Island: http://projects.intellimedia.ncsu.edu/crystalisland/

ELASTIC3S: Embodied Learning Augmented through Simulation Theaters for Interacting with Cross-Cutting Concepts in Science:
http://stemforall2017.videohall.com/presentations/973

2. Learning Analytics for Assessment

Analytics
for Assessment

By Jodi Asbell-Clarke and Judith Fusco

Method Description, Motivation, and Conjectures

Digital learning environments such as games and cognitive tutors collect time-stamped user actions (e.g., mouse clicks and keystrokes). The resulting clickstream is a digital log that can be analyzed to understand learners and make predictions about what they know and can do. One important strand of cyberlearning methods involves using this novel capability for ongoing formative assessment to improve teaching and learning. Formative assessment is the process of using evidence of students' understanding to make decisions about how to support their next steps in learning. Thus, in the same way that Facebook or Amazon uses consumer clickstream behavior to predict future purchases, education data mining identifies patterns of gameplay that predict future student learning. By integrating this information into instruction, teachers and designers can leverage gameplay to improve explicit learning and teaching afterwards.

When educators implement formative assessment well, teaching and learning become better adapted to students' learning needs. The typical method for gathering formative assessment data is to give students tests – but students don't like taking tests and teachers regret how much time testing takes away from instruction. What if games and other interactive activities could provide the necessary data without students having to take tests?

- **Computer science innovation:** Developing new data analysis techniques to make sense of data that are automatically collected as students play games
- **Learning science innovation:** Connecting "implicit" to "explicit" learning so as to integrate games and classroom instruction into an adaptive learning system

Cyberlearnign researchers have proposed "stealth assessments" that measure what students know and can do without giving them a typical test-taking experience (Shute & Ventura, 2013). To develop this idea into a workable technique, researchers are expanding education data mining methods (and closely related learning analytics methods) to find meaning in logs of user data from interactive games and other digital activities. A series of key insights are emerging around the relationship between implicit learning (activities that are not consciously planned or recognized as learning) and explicit learning (activities that overtly intend to promote learning). Researchers are exploring how measurements of implicit learning through education data mining can become a foundation for school-based explicit learning. To do so, they are building a convergent science that synthesizes theories and evidence from psychologists, neuroscientists, and other disciplines (Rowe et al., 2017). Early findings are promising: researchers have found that learning analytics can enable teachers to efficiently adapt the environment so that learners can have experiences optimized to their own learning needs or behaviors (Ke & Shute, 2015).

Examples of Projects Using Learning Analytics for Assessment

Earlier experimentation in learning analytics was conducted with structured, predictable environments such as solving puzzles, logic, or math problems. Intelligent tutor systems were developed to analyze students' progress on these structured problems and to give students feedback and guidance to advance their learning (Ritter, Anderson, Koedinger & Corbett, 2007). Overall, research on intelligent tutoring systems has established that these systems can deliver meaningful and positive impacts on learning (Van Lehn, 2011). Cyberlearning projects also feature less structured environments such as digital learning games. The lack of structure in these environments presents a research challenge but also an opportunity for rapid advances.

For example, researchers at Educational Gaming Environments (EdGE) at TERC have built free-choice games to support and measure STEM learning in context (NSF #1119144, #1502882). The EdGE team builds on the game mechanics (the structure of goals and rules) of familiar games that many people choose to play in their free time. To make learning games, the team adds new scientific content to the games. For example, EdGE studied high school students who played **Impulse**, a game that follows Newton's laws of motions. Players use a force (a click on the screen) to move their green ball to the goal without colliding with any other balls. The different-colored balls have different mass, so they react differently to the force.

EdGE games are designed to collect data on players' behaviors that the researchers can study as evidence of how the students learn science. Researchers observed players using software that records the players' screens as well as their audio and video from the computer's camera (see Multimodal Analysis, above). As students played and thought aloud with a partner, researchers noted when the learners were behaving and discussing behaviors consistent with relevant science understandings.

Impulse - a game of Newtonian physics.

Used with permission of Jodi Asbell-Clarke.

Screen and video recording for observations and human coding.

Used with permission of Jodi Asbell-Clarke.

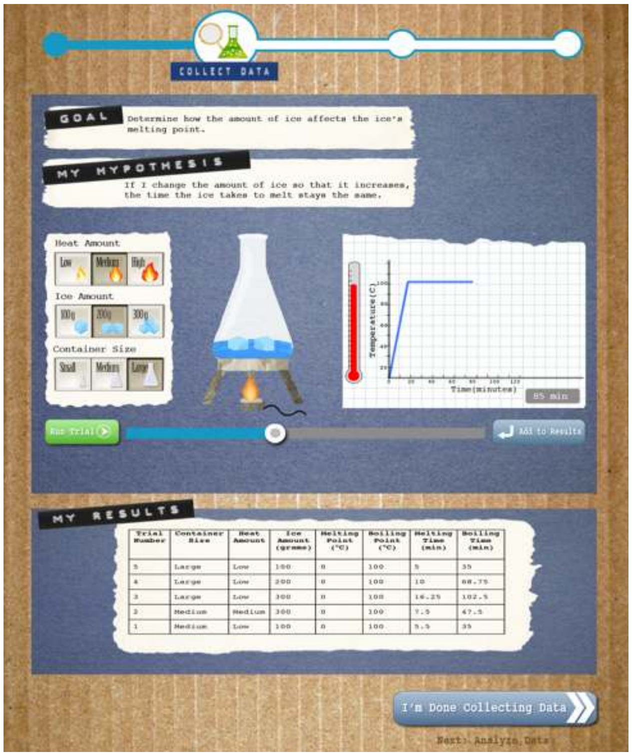
Researchers found that data mining models were able to detect when players learned to treat heavier balls with more force than light balls. Surprisingly, students learned this even though Newton's second law (Force = mass*acceleration) was not taught explicitly in the game. Teachers were later able to build on this implicit learning about the second law in the classroom, formalizing what students had learning intuitively. To do so, they used additional materials as a bridge that connected examples from the game to related content taught explicitly in class. This research established that students who built game strategies related to Newton's second law and then were in classes where teachers bridged game learning to classroom learning performed better on a test of their physics knowledge (controlling for what they knew before the game experience).

Next, the EdGE researchers explored games where performance in the game could serve as a stealth assessment of learning. While attempting to design a scoring system that could reflect students' knowledge, the researchers recognized that it was *how* players solved problems in the game that mattered, not *if* they solved the problem. In a complex, action game like Impulse, however, there were too many options to score. Education data mining offered an emergent solution. By designing the data collection, distillation, and organization in ways that were informed by extensive observations of players' gameplay, researchers were then able to build data mining models that could comb through massive streams of data to reliably detect patterns of how learners played the game that were predictive of how much they had learned implicitly.

In addition, the information from real-time game-based assessments can be fed into dashboard tools. Teachers can use the dashboard to decide what types of teaching strategies to use and when. Learners can use the dashboard for self-monitoring and metacognition. Designers can use game-based assessments to customize the learning experience for each different player. Now, EdGE is working with researchers from Landmark College and Massachusetts Institute of Technology to build even more sophisticated multimodal models of implicit learning that integrate game-based learning assessment data with other digital data from eye-trackers, electroencephalogram, and physiological sensors (NSF #1417967).

In another example of a cyberlearning project that connected learning analytics to formative assessment, Janice Gobert and colleagues created a web-based learning environment, **Inquiry Intelligent Tutoring System** (Inq-ITS) (U.S. Department of Education #R305A120778, NSF #1252477) in which middle school students show what they know about inquiry using simulations while their work is assessed in real time (see sidebar From Project to Product). **Inq-Blotter** (NSF #1629045; ED-IES-16-C-0014; ED-IES-15-C-0018), a related tool, sends information via alerts to teachers' tablets and phones. From these just-in-time alerts, teachers can know who needs help and what specific scientific practices they need help with. Scientiifc inquiry is a difficult topic to teach as it involves many complex steps and concepts. Continuous assessment and the right help at the right time can make it easier for students to learn about inquiry. Researchers are using learning analytic methods with the data from these tools to provide faster and more targeted formative assessments than were possible with traditional quizzes or by questioning students.

A simulated science lab in Inq-ITS guides student inquiry.



GOAL Determine how the amount of ice affects the ice's melting point.

MY HYPOTHESIS If I change the amount of ice so that it increases, the time the ice takes to melt stays the same.

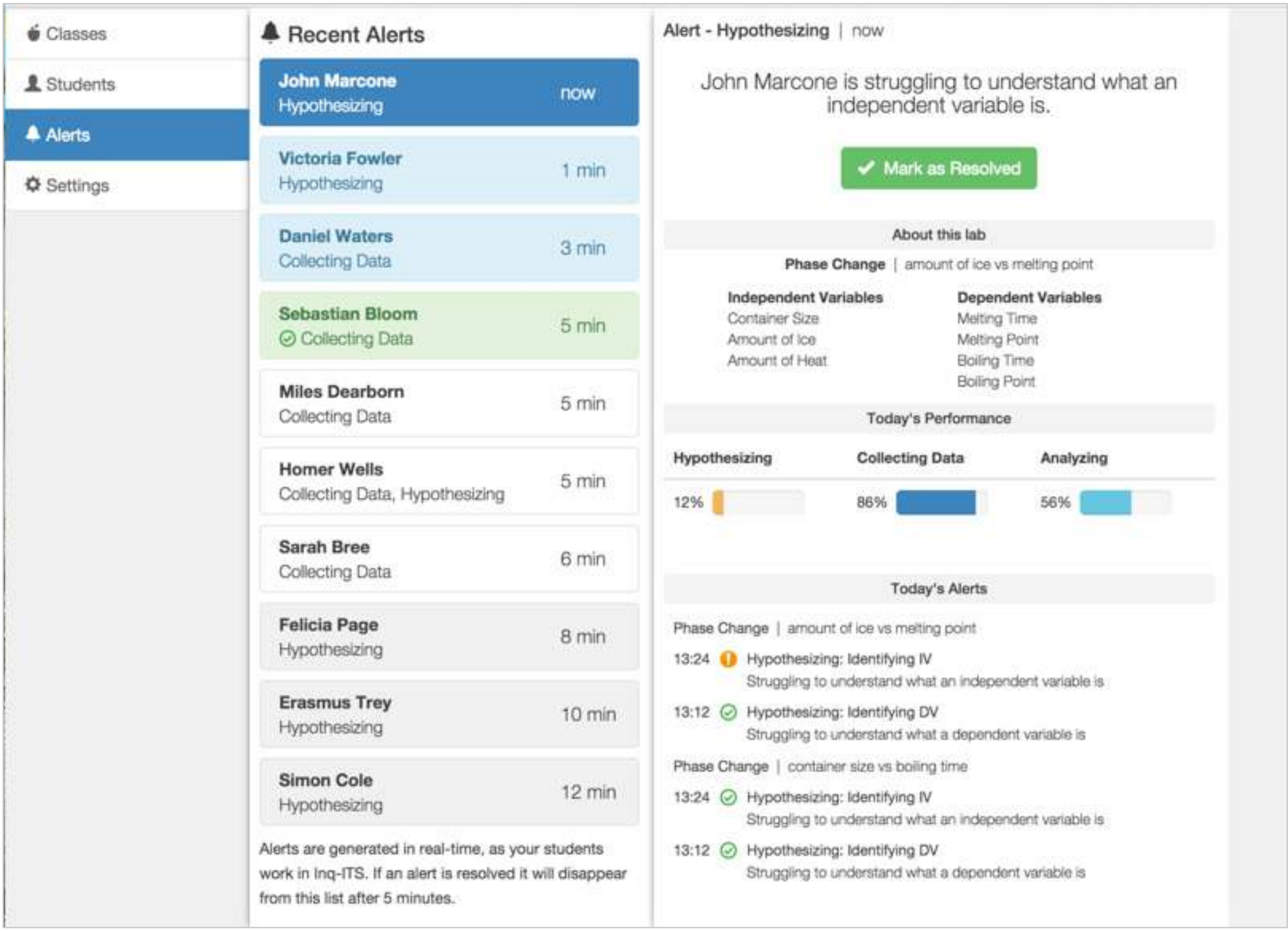
MY RESULTS

Trial Number	Container Size	Heat Amount	Ice Amount (grams)	Melting Point (°C)	Boiling Point (°C)	Melting Time (min)	Boiling Time (min)
5	Large	Low	100	0	100	5	35
4	Large	Low	200	0	100	10	68.75
3	Large	Low	300	0	100	16.25	102.5
2	Medium	Medium	300	0	100	7.5	47.5
1	Medium	Low	100	0	100	5.5	35

Used with permission of Janice Gobert.

Also, Emma Mercier in the C-STEPS project, described on page 42, is using learning analytics to improve the teaching of collaborative problem solving in an undergraduate introductory engineering course. The project researchers are building tools for teaching assistants to help manage classroom technologies and trying to understand how to help groups with content or collaborative processes. The researchers are also developing methods to find instances of collaboration among groups of three or four students working with their own tablets. The tablets are synchronized so that edits, such as drawing figures or text, are immediately shown on the tablets of the other students in the group. Methods are being developed for detecting when groups are not making progress or when one person is doing all the work. The data obtained will be used to create visualizations for instructors so they can intervene to answer questions or encourage effective collaboration. The project should result in new learning analytics can help researchers evaluate the collaboration practices and also, more practically, help teaching assistants more successfully implement collaborative problem solving.

Inq-Blotter dashboard for teachers showing students' progress and understanding on NGSS (Next Generation Science Standards) practices.



Recent Alerts

John Marcone	Hypothesizing	now
Victoria Fowler	Hypothesizing	1 min
Daniel Waters	Collecting Data	3 min
Sebastian Bloom	✓ Collecting Data	5 min
Miles Dearborn	Collecting Data	5 min
Homer Wells	Collecting Data, Hypothesizing	5 min
Sarah Bree	Collecting Data	6 min
Felicia Page	Hypothesizing	8 min
Erasmus Trey	Hypothesizing	10 min
Simon Cole	Hypothesizing	12 min

Alerts are generated in real-time, as your students work in Inq-ITS. If an alert is resolved it will disappear from this list after 5 minutes.

Alert - Hypothesizing | now

John Marcone is struggling to understand what an independent variable is.

About this lab

Phase Change | amount of ice vs melting point

Independent Variables	**Dependent Variables**
Container Size	Melting Time
Amount of Ice	Melting Point
Amount of Heat	Boiling Time
	Boiling Point

Today's Performance

Hypothesizing	**Collecting Data**	**Analyzing**
12%	86%	56%

Today's Alerts

Phase Change | amount of ice vs melting point

13:24 Hypothesizing: Identifying IV
Struggling to understand what an independent variable is

13:12 ✓ Hypothesizing: Identifying DV
Struggling to understand what a dependent variable is

Phase Change | container size vs boiling time

13:24 ✓ Hypothesizing: Identifying IV
Struggling to understand what an independent variable is

13:12 ✓ Hypothesizing: Identifying DV
Struggling to understand what a dependent variable is

Used with permission of Janice Gobert.

Contributions, Opportunities, and Challenges

Interest in education data mining and learning analytics for formative assessment is growing because these methods address teachers' desire for less overt testing but also their need for more timely and useful information about how students are learning. Solving this problem requires convergent science that brings together researchers in computer science, education data mining, formative assessment, STEM disciplines, game-based learning, and learning sciences extending to cognitive psychology and neuroscience.

This work is in an early but promising stage. Important challenges include the following:

- How to combine automatically collected data with teacher observations to generate more robust estimates of what students know and can do.
- How to interpret log data (which are quite detailed) in terms of broader patterns, which are more useful for instructional decision making.
- How to integrate these techniques into the classroom without their becoming intrusive or disruptive to successful classroom practices.

- How to use the information to engage at-risk learners and better support students who have trouble expressing what they know on traditional assessments.

Learning analytics researchers continue to investigate the role of the teacher and understand what can and cannot be included in digital learning environments. One tension is to balance the human and digital sides and support each side in what it does best. A further opportunity is to find the right ways to bridge the human and digital sides, possibly through virtual coaches or robotic agents that use the analytics to contribute to interactions between a student and a teacher.

Resources

CIRCL Primer: Educational Data Mining and Learning Analytics:
http://circlcenter.org/educational-data-mining-learning-analytics/

Research on Computational Thinking & the Game Zoombinis:
http://stemforall2017.videohall.com/presentations/903

Inq-ITS website: http://www.inqits.com

3. User- and Community-Centered Design Methods

User and Community-Centered Design

by Amy Ogan

Description of Method, Motivation, and Conjectures

User- and community-centered design methods have similar innovation potential in computer science and the learning sciences because both fields have much to gain from involving users in the design process. Too often innovative technology turns out not to be appealing, usable, or valuable to its target audience. User- and community-design methods seek to change this by finding ways to better engage members of the audience in shaping the tools they will use. One particularly productive focus has been on methods for designing technologies for young learners and for learners with special needs. Issues of accessibility for learners and users who are blind, hard of hearing, or have physical mobility challenges are central to both fields. Similarly, equity and access for underserved urban and rural communities, those in the Global South, and marginalized communities in the United States have increasingly become a focus, driving research that will ultimately benefit all users.

- **Computer science innovation:** Design of methods that engage users and user communities in shaping the technology they will use
- **Learning science innovation:** Design of methods that engage learners and learning communities in shaping the technology they will use

To advance these methods, cyberlearning research is building on strong ties to computer-human interaction (CHI or HCI) research. For example, the CHI Kids community frequently explores novel interactions with youth in informal environments, as does the ACM Interaction Design & Children conference. A second strong tie is more deeply grounded in the learning sciences. Design-based research (Brown, 1992; Hoadley, 2002) is learning sciences methodology that rigorously explores which design features have the most potential to improve learning. In design-based research, novel learning tools are conceptualized and then tested multiple times in real- world environments so that designers can make improvements as they see the tool in use over time. This iterative approach also enables researchers to improve learning theories in natural settings, which can lead to new theories and frameworks for understanding learning, teaching, and educational policy (Zimmerman, Forlizzi, & Evenson, 2007).

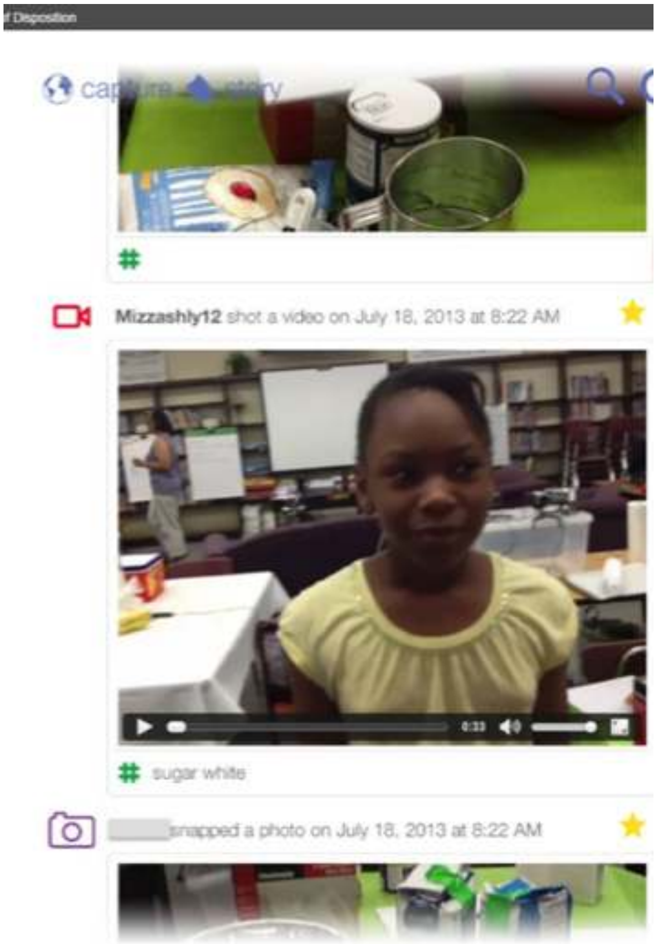
In addition, opportunities for cross-pollination can also be found where the two fields diverge. Typically, HCI work focuses on efforts to make interactions with technology simple, pleasant, and easy to accomplish. For example, users should be able to find and purchase the product they want on a website in a minimum of steps while feeling good about their purchase. Often in cyberlearning projects, however, the goal is to achieve the very opposite. The notion of "desirable difficulties" (Bjork, 1994) introduces an interesting challenge to a typical human-computer interaction. Sometimes the goal of a cyberlearning intervention is to present learners with problems that they need to struggle with and resolve, leading them to deeper understandings (e.g., Lehman, D'Mello, & Graesser, 2012). The idea of focusing on desirable difficulties has the potential to lead to more general advances in HCI, for example, in the domain of mindful computing (building awareness of one's digital interactions rather than being absorbed by them), or where enjoyment necessitates overcoming challenge, such as digital gaming or tools for solving problems in do-it-yourself projects.

Examples of Cyberlearning Projects that Integrate HCI Methods

The following two projects incorporate many cyberlearning features described in other sections of this report, such as designing for communities of learners, digitally augmenting the classroom, and conducting multimodal analysis; here, we look at how they specifically relate to design methods.

In the project **ScienceKit for Science Everywhere: A Seamless Scientizing Ecosystem for Raising Scientifically Minded Children** (NSF #1441523), June Ahn, Tammy Clegg, and Jason Yipp created a social media app that uses public displays to allow young learners to share their science queries, ideas, and observations as they go about their daily life. The project asks how a neighborhood ecosystem (such as middle school teachers, afterschool programs in a church, and others) could support these students in everyday science learning. It consists of a stream of kids' posts from their social media feed (pictures, hypotheses, everyday science questions) displayed on large touch screens in public spaces. With these screens, adults and community members can give feedback or know more about what activities the children are undertaking.

Social media feed of ScienceKit.



Mizzashly12 shot a video on July 18, 2013 at 8:22 AM

[redacted] snapped a photo on July 18, 2013 at 8:22 AM

Used with permission of June Ahn.

The researchers asked, How could technology connect previously isolated learning experiences? They found that adults could recognize potential in what they were noticing in these everyday student interactions but that they had trouble figuring out what to do to improve learning (for example, a parent might ask, “My kid likes soccer, not science…so how can I use this stream to talk about science in soccer?”). The design-based research process led the researchers to design in-person “family nights” to help parents develop strategies for framing everyday activities like soccer as opportunities to learn science.

In another project, **Teaching Intercultural Competence through Personal Informatics** (NSF #1464204), Amy Ogan and John Zimmerman investigated how to provide teaching assistants in higher education with fast, accurate feedback on their own classroom performance in order to help them learn (www.amyogan.com). Moving away from large lectures and increasing student engagement and participation in classrooms significantly improves learning, but teaching assistants need considerable support to make this change. This project addresses this systemic problem through the development of a new genre of technology: Smart Professional Development (SmartPD). SmartPD consists of an interconnected set of systems that help instructors use *near-real-time classroom data.* This SmartPD genre draws on technical and sociotechnical advances in sensing arrays, computer vision, intelligent environments, and HCI advances such as personal informatics, as well as frameworks of professional development in higher education.

In a design-based research study of a semester-long course, researchers found that a discrepancy between the instructors’ expectations about their classrooms and the actual outcomes motivated the instructors to engage more deeply with their own data. But they needed more than motivation and data; instructors needed supportive strategies to help them improve their practice. Without such strategies, instructors felt discouraged and defaulted to a teacher-oriented perspective. The design innovation of introducing brief but frequent messages with suggested teaching strategies led to greater self-efficacy as a teacher.

ClassInSight uses modern sensors to track student attendance, participation, facial expressions, and hand raises.

Used with permission of Amy Ogan.

In both these cases, close work with the audience for an innovation led to additional design improvements that were necessary for effective use of the system to advance learning.

Contributions, Challenges, and Opportunities

Cyberlearning projects that are using user- and community-oriented design methods are demonstrating how learning and computing researchers can work together to make technologies that are more appealing, usable, and effective. Given the complementary perspectives of HCI and cyberlearning research, it makes sense to continue to work on a unified design process that can build on the commonalities in research and design methods — and guide better uses of the different aspects of interaction that each specialty focuses on.

In addition, there are common challenges and opportunities worth tackling. Both fields need to grapple with issues of privacy and ethics in collecting, sharing, and displaying personal information. Both are working to coordinate multiple kinds of technologies to gather and analyze large-scale data in order to improve their designs. What is clear is that the method of involving the target users and communities throughout each stage of the design process, listening to their concerns, and addressing their needs is key to developing programs and technologies that help solve problems and provide new learning opportunities.

Resources

Science Everywhere: engaging entire communities in STEM learning with technology: http://stemforall2016.videohall.com/presentations/775

CIRCL Primer: Design-Based Implementation Research: http://circlcenter.org/dbir/

From Project to Product

At its best, cyberlearning research often occurs in "Pasteur's Quadrant" (Stokes, 2011) —research that advances foundational understanding while also solving societal problems. Cyberlearning research in this quadrant both advances foundational understanding of learning and develops technologies that can have immediate value for learners. Historically, many early cyberlearning technologies have hit this mark, including Logo, Scratch, intelligent tutor systems, and dynamic geometry tools — all of which led both to important bodies of scientific literature as well as technologies that are widely used by educators and learners.

The dual goals of insight and impact are supported by U.S. government legislation and programs. The Bayh-Dole Act (in effect since 1980) recognized that the federal government, which had until then been the owner of the inventions it funded, was not in the best position to bring products to market. The act encourages researchers and inventors working at universities, nonprofit organizations, or small businesses to obtain patents for their innovations and to lead commercialization efforts.

Commercialization can be funded through such programs as the Small Business Innovation Research (SBIR) program, which gives grants to small companies to build products based on sound research. SBIR programs are available at many federal agencies including NSF, the U.S. Department of Education, and the National Institutes of Health. Further, NSF's Innovation Corps (I-Corps) program prepares NSF principal investigators to become entrepreneurs and learn how to turn their ideas and inventions into marketable products or services. Additionally, commercialization can also be supported by today's vibrant education venture and accelerator sector, which gives innovators funding and support to develop businesses that offer learning innovations at scale.

Janice Gobert is one example of a current cyberlearning researcher who has started a business, Apprendis (apprendis.com), to commercialize her innovations, Inq-ITS and Inq-Blotter. Gobert and colleagues first developed their core approach with NSF funding (NSF #0733286, #1008649, #0742503, #1252477, #1629045) and U.S. Department of Education funding (R305A090170, R305A120778). Later, working with the technology transfer office at Worcester Polytechnic Institute, where she was a professor, Gobert and colleagues started Apprendis and obtained the patents for their inventions. Apprendis received Phase 1 and Phase 2 SBIR grants from the U.S. Department of Education (ED-IES-15-C-0018, ED-IES-16-C-0014). Inq-ITS is now commercially available to teachers across the country. As the business has grown, Gobert has found that balancing her responsibilities as a professor, researcher, and CEO of a company can be a challenge. However, she insists that it is essential for the founders to maintain control of the product to ensure that the learning innovation is high quality and not watered down for the sake of increasing short-term profits. According to Gobert, "Cyberlearning community members are doing really good and innovative work. They should commercialize. We don't want products out there that aren't based on research. If we don't do it, who will?" (J. Gobert, personal communication, June 8, 2017).

The Cyberlearning Community: A Broader Look

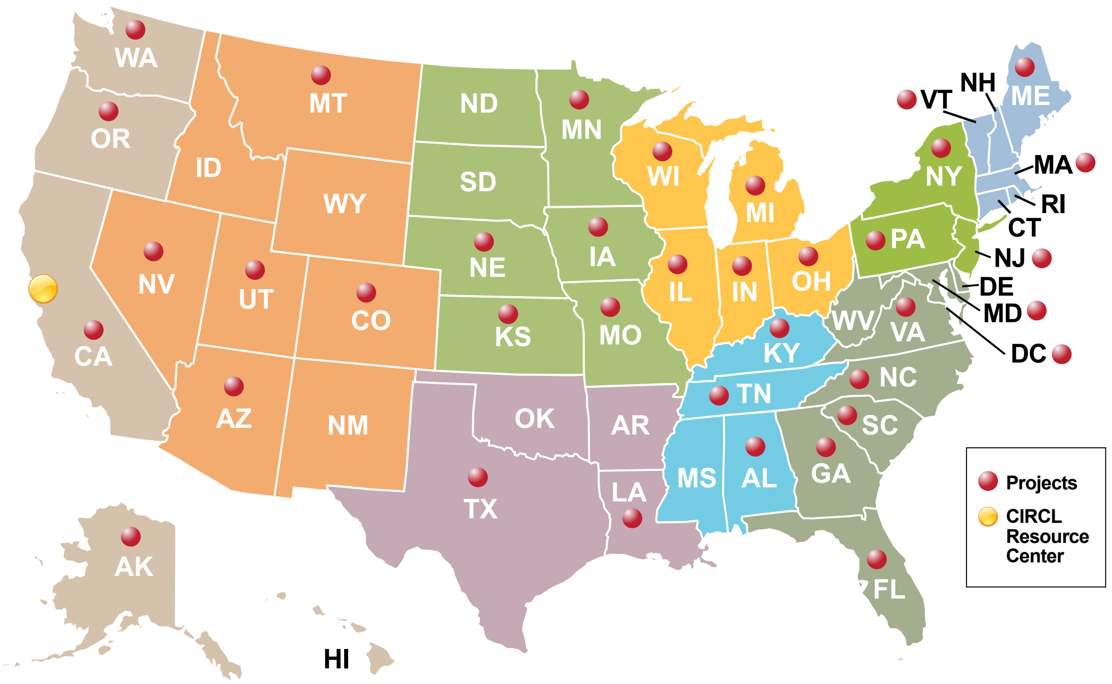
by Shari Gardner

NSF released its first call for cyberlearning proposals in 2010. The program was initially called Cyberlearning: Transforming Education and is now called Cyberlearning and Future Learning Technologies (CFLT). From 2010 through summer 2017, the cyberlearning program made 279 awards. So far, this report has focused on six design innovations and three methodological innovations but does not comprehensively summarize the research and development advances throughout the cyberlearning portfolio. This section provides a broader view of the portfolio and discusses the role of the Center for Innovative Research in Cyberlearning.

The Current NSF Cyberlearning Portfolio

The NSF cyberlearning portfolio includes projects across the United States. As befits the intention to fund early stage research, many of the grants have been for Exploration projects (31%), with considerably fewer at the Development and Implementation (18%) or Integrations level (2%). In addition to projects funded by one of the cyberlearning programs (38%), projects with a cyberlearning focus were funded by other NSF programs (62%). As of this writing, a total of 728

NSF-funded cyberlearning projects are located across the United States.



Source: Data from National Science Foundation.

Cyberlearning and cyberlearning-related awards have been made across NSF.

NSF cyberlearning projects are focused on both school and informal learning contexts, such as museums, community-based organizations, or smart and connected communities. Most researchers are designing and building some form of new tool, and many address not only how to support learners, but also how to support their instructors and mentors. Cyberlearning projects span the spectrum of lifelong learning, from preschool to adulthood. There is a balance between projects that emphasize K–12 learners and those that emphasize adult learners, with a majority of projects focusing on middle school through college.

Cyberlearning projects also tackle a range of subjects. Science, computer science, mathematics, and engineering are most often the focus, but projects go beyond STEM subjects to include the social sciences and reading. Overall, the portfolio has exceeded the expectations the NSF Task Force on Cyberlearning set in its 2008 report, *Fostering Learning in the Networked World: The Cyberlearning Opportunity and Challenge,* which set the stage for NSF's investments in this new domain. For example, the current emphasis on embodied learning, data science education, multimodal analytics, and making activities was not yet on the horizon in the 2008 report.

Broadening Participation and Graduate Student Training

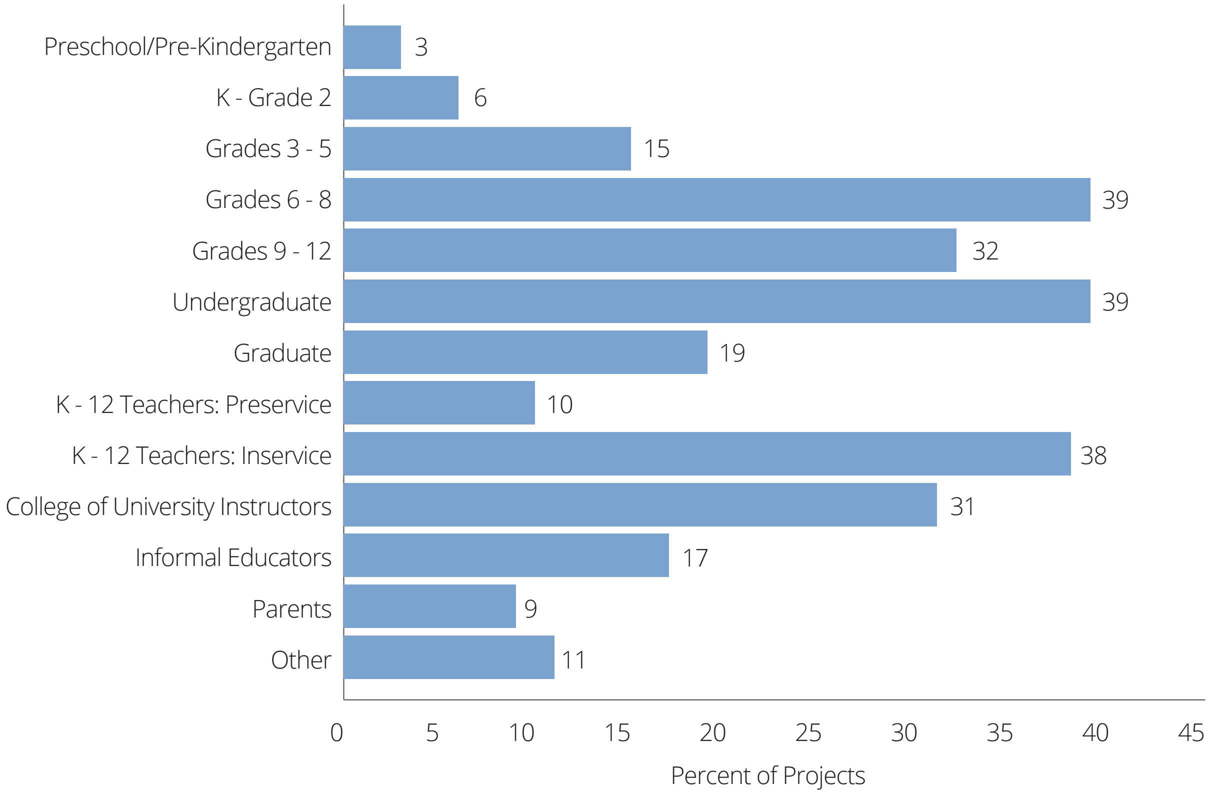
In the Introduction, we noted that cyberlearning researchers share a commitment to equity. Evidence for this claim comes from the number of awardees who reported serving underrepresented minorities (41%), women and girls (30%), schools where a majority of students live in poverty (29%), English language learners (17%), and students who need special education services (5%).

Cyberlearning projects also build capacity by training graduate students. Nearly 70% of projects train at least one graduate student. In general, students who work on cyberlearning projects are learning multidisciplinary research (or convergent science) skills. The degrees being pursued most commonly are computer science (35%), with learning sciences (16%) or cognitive science/psychology (16%) close behind. Graduate students participating on cyberlearning projects are also pursuing degrees in digital communications, social sciences, education, engineering, and the life sciences. Roughly two-thirds are pursuing an academic career, but more than one-third are interested in industry careers — and many graduate students are considering more than one career trajectory.

The NSF cyberlearning program has emphasized expanding the opportunities for computer scientists and learning researchers to collaborate on developing new learning technologies. A recent survey showed that 71% of projects with a multidisciplinary team included a computer scientist. As noted in the Methods section, collaborations are advancing research in three key areas: methods for conducting human-computer interaction research at the frontiers with diverse communities of participants, tools and methods for multimodal analytics, and automated techniques for data collection and analysis for assessment of student learning.

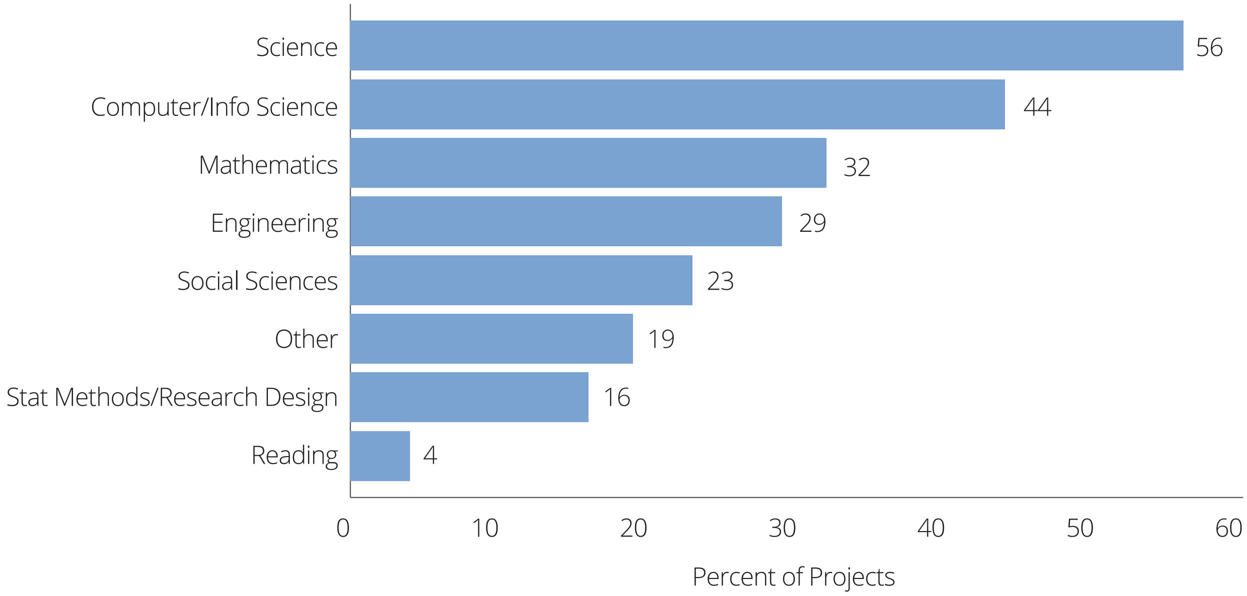
Cyberlearning awards have also helped to grow the field by making grants to new principal investigators (26%) or to principal investigators with only one or two prior awards (22%), although many have also gone to more seasoned researchers.

Cyberlearning projects span the spectrum of lifelong learning.



Source: CIRCL Intake Surveys. Note: respondents (N = 177) could select more than one response.

Cyberlearning projects address a wide-range of disciplines.



Source: CIRCL Intake Surveys. Note: respondents (N = 294) could select more than one response.

What Cyberlearning Researchers Are Saying About Their Community

I think the cyberlearning community is incredibly valuable in the way that it acts as a multifaceted broker, connecting researchers across disciplines (learning scientists, computer scientists, educational psychologists, designers, and more) who find a welcoming venue to share ideas and insights, as well as connecting those researchers to practitioners with whom they collaborate, mutually inspire, and develop real solutions that can transform learning with technology.

—Amy Ogan, Carnegie Mellon University

Cyberlearning plays a role not entirely dissimilar to the FDA or NIH – the programs it funds and research that comes out of the community represent objective, reliable, and unbiased findings that can help schools, parents, commercial companies, and learners. It can help by both providing educational tools that are supported by rigorous research, but also in helping everyone better understand how to design and use technology in education.

—H. Chad Lane, University of Illinois at Urbana-Champaign

First let me say that in some respects, I feel like I "grew up" with the values and the aims of the cyberlearning program.…As a student of Learning Sciences and Technology Design, it [cyberlearning] was a perfect fit with my doctoral program and the promise of a new field of research. [The Cyberlearning program supports] fantastically interdisciplinary and innovation-focused projects…; it changed my whole view of what kinds of research could be proposed and who I would seek out to work with on new projects.

—Robb Lindgren, University of Illinois

Being a part of the cyberlearning community feels like a natural home for someone like me; I care deeply about learning and also how leveraging technology and digital media can connect young people's experiences across settings to make learning more relevant to their daily lives. The cyberlearning community is empirically-driven but also eager to push the edges of innovation in studying and designing teaching and learning settings.

—Katie Headrick Taylor, University of Washington

Cyberlearning is an incredible community because it is a meta-community of meta-learners: we work on creating real, social opportunities for learners, and the community works hard to teach, mentor, and communicate with each other. In our theory and practice, there is a real attention to seeing what could be next and a commitment to making a future in which education is more equitable, more connected, and more thoughtful.

—Matthew Berland,
University of Wisconsin-Madison

Cyberlearning has provided a "home" for a unique and important realm of work: examples of the power of focusing on both technology design and the learning sciences. The result is something unique. The examples and community Cyberlearning has fostered stand as a singular testimony to the importance of taking both design and learning seriously and supporting them in combination. Other NSF programs could do well to borrow from

Cyberlearning's intentional focus, especially on technology development, and on the value of deliberately sustaining a top-notch community surrounding it.

— Chad Dorsey, Concord Consortium

The Role of the Center for Innovative Research in Cyberlearning

The Center for Innovative Research in Cyberlearning (CIRCL) was launched with NSF support in April 2013 (NSF #1233722). CIRCL's overall goals are to amplify research impact, broker connections, broaden participation, and facilitate collaboration among cyberlearning researchers. The community has been defined thematically to include projects funded by NSF's Cyberlearning program or with a cyberlearning theme, as well as educators, industry representatives, and government officials who have a stake in the results of this research. CIRCL is led by SRI International in collaboration with Education Development Center, Inc. (EDC), NORC at the University of Chicago, and Digital Promise.

CIRCL has hosted five major annual meetings to date, as well as many smaller face-to-face and virtual events. CIRCL meetings are interactive, interdisciplinary, and participatory. The community is involved in both conceptualizing and executing the events. By hosting innovative events and recruiting thought-provoking speakers, CIRCL catalyzed investigators in the field to envision new possibilities for achieving broader impact. In 2016–17, six CIRCL events engaged more than 800 participants: Cyberlearning 2017, Cyberlearning 2016, the Smart and Connected Communities Innovation Lab, the Active Learning Symposium, the Next Generation High School Summit, and an international workshop at the 2016 European Conference on Technology Enhanced Learning (EC-TEL) in Lyon, France. Participants included funded principal investigators (about half the participants) as well as teachers, graduate students, postdoctoral students, accessibility specialists, museum staff, and industry representatives. CIRCL also created a buddy program to ensure more diversity among participants. In addition, CIRCL has held a series of in-person proposal writing workshops with the goal of increasing the diversity of cyberlearning principal investigators, and it works with teachers in a fellowship program each summer.

High-profile publications by CIRCL staff include the 2015 *Innovating Pedagogy* report--developed together with colleagues at Open University, which was downloaded more than 75,000 times in the first year of its release (Sharples et al., 2015). CIRCL staff also wrote the article "Smart & Connected Communities for Learning" published in *Computing Research News* by the Computer Research Association (Roschelle, 2016), developed a section of the U.S. National Educational Technology Plan (Office of Educational Technology, 2017), and wrote an entry on cyberlearning in the *Sage Encyclopedia* *of Out-of-School Learning* (Roschelle & Michalchik, 2017). In 2016, CIRCL was invited to present at the White House EdTech Symposium and was asked to join Digital Promise's research advisory group, thus interfacing between cyberlearning research and Digital Promise's League of Innovative Schools. CIRCL leader Jeremy Roschelle recently joined Digital Promise, which will expand the connections between networks of cyberlearning researchers and networks of innovative schools.

The CIRCL website (circlcenter.org) has even broader reach, with its more than 650 pages, which includes 65 researcher perspectives, 22 project spotlights, 21 primers on key research topics, 38 archived CIRCL events (virtual and face to face), 25 newsletters, more than 200 project abstracts, and many other resources for researchers and practitioners. The website is one-stop shopping for stakeholders wanting to get a better sense of the breadth of cyberlearning research. CIRCL videos have received more than 55,000 views across 145 countries, and CIRL collaborated with other resource centers on two annual video showcases of NSF-funded research that together attracted about 50,000 participants. CIRCL has hosted 22 topical webinars and proposal writing workshops to help broaden participation in cyberlearning research. Videos and other archived records from CIRCL events are available on the website.

CIRCL staff also help cyberlearning investigators find new collaborators. In response to email requests alone, CIRCL brokered more than 40 direct connections for writing proposals and finding additional project expertise in 2016 (more than 100 connections brokered, cumulatively). CIRCL also recruits diverse stakeholders to contribute to key activities (e.g., writing primers, serving as mentors and event program committee members, nominating buddies) thus broadening participation and building strong networks. CIRCL also maintains a social media presence on Facebook (CIRCLCenter) and Twitter (@ CIRCLCenter) and through its newsletter. To learn more about CIRCL, visit **circlcenter.org**.

Resources

2015 Innovating Pedagogy Report: https://www.sri.com/work/publications/innovating-pedagogy-2015

Innovation Lab Maps the Future of Learning in Smart and Connected Communities: http://cra.org/crn/2016/06/innovation-lab-maps-future-learning-smart-connected-communities/

National Educational Technology Plan: https://tech.ed.gov/netp

Digital Promise: http://digitalpromise.org/

Toward Strategic Impact: Cyberlearning and Big Ideas

Cyberlearning research has deep roots in past research but also looks beyond today's most common education technologies toward tomorrow's emerging technologies for learning.

Today, education technology has become essential infrastructure in schools and universities, often in the form of hardware such as laptops, tablets, and smartphones, but also as learning management systems, online content, and cloud-based instructional tools. The selection, integration, and effective use of this generation of technology-enhanced learning remain important societal challenges. Yet within a decade, new technologies may supersede those that are commonplace today.

In 1989, it would have been difficult to imagine how broad the use of the World Wide Web would become in education. Before 2007, it would have been difficult to imagine the possibility of so many students carrying a touch-based, mobile, always-connected device like tablet computer or smartphone in their backpack. It is important that we do not assume a smooth extrapolation from today's technologies to those of tomorrow. Cyberlearning research builds from the premise that dramatic change in learning with technology will only accelerate. Six illustrative designs for dramatically different technologies and three methods for investigating learning are highlighted in this report, and these nine themes are just a sample of frontiers being explored through cyberlearning research projects.

One way to summarize the themes is to look at how they build on cyberlearning commitments (as discussed in the Introduction) and thus move beyond commonplace technologies. One commitment is to *orient toward the horizon.* The design themes are tackling this by conducting research with artificial intelligence-based personal assistants and also with augmented reality and remote presence technologies. Likewise, the designs go beyond conventional forms of input and output to consider a range of mobile, touch, and sensor-based tools.

Another commitment is to *equity*, and this permeates the themes in the form of design methods that engage students with special needs and learners in low-income settings. Another example is the effort going into the development of sophisticated scientific labs that are accessible in rural and underserved communities. Likewise, the commitment to equity is evident in research questions about language use, such as how switching between dialect and more standard forms of English can help learners.

The commitment to *community-centered learning* is active in multiple forms as well. Classroom communities investigate scientific phenomena together. Neighborhood communities use digital mobile maps to navigate and connect learning opportunities. The commitment to learners as producers and creators is highly evident in the designs for expressive and playful learning, sketching with touch interfaces, and mapping tools. Along with the methodological commitments to *convergent science* and *design-based research,* cyberlearning research is producing a portfolio of learning designs that go well beyond what is commonplace in classrooms today.

A different kind of summary would look for the impact of the new designs. As discussed in the Introduction, cyberlearning research is early-stage research. Not surprisingly, much of the initial impact is methodological — finding new ways to measure and study learning. For example, many of the projects are generating multiple streams of data about learning that include information about gesture, gaze, emotion, keystrokes, and clicks, as well as audio and video records of what learners are doing and saying. On the path to understanding learning impacts, a necessary first step is finding ways to organize, analyze, and make sense these new data.

In addition, some cyberlearning research is showing promise of moving the needle on learning outcomes. Here are a few insights that could lead, down the road, to efficacy results:

- Informal sketches and animations can enable students to focus on relationships and patterns and thus develop deeper and more complex understanding of scientific ideas.
- Journalism activities can provide open-ended yet rigorous opportunities to test theories, while enabling students to develop agency and identity as citizens who do science to help their communities.
- Activities that encourage embodied cognition, for example in digital performance spaces, can have a positive impact on student participation, attitudes, and opportunities to do scientific inquiry (relative to more conventional science classroom activities).
- A personal assistant that can build rapport with students enables struggling students to engage in scientific reasoning.
- Multi-touch table interfaces increase the quality and quantity of conversations in small groups of learners.
- Students learn more from games when bridging activities connect implicit to explicit learning.

Complementary findings highlight the key conditions and practices that must be in place for technology-based interventions to have an effect. Throughout the designs, researchers are finding that learning also depends on such factors as the design of the curricular activity, the teacher's involvement, and the support provided to teachers. Further, the research community is developing shared user- and community-centered methods to better address a comprehensive set of design requirements.

Cyberlearning researchers are eloquent about the value of the opportunities to do exploratory, early-stage, convergent research (see What Cyberlearning Researchers Are Saying About Their Community). Cyberlearning funding gives researchers freedom to break from the conventions of today's classrooms or museums — for example, to envision classrooms as performance spaces or to conceptualize physical community space as a learning resource. It also gives researchers the freedom to develop the theoretical concepts — affect, peer coaching, authenticity, and identity — needed to guide and understand the future of learning. Likewise, cyberlearning researchers have the freedom to go beyond canonical social science research methods to investigate new approaches such as multimodal analysis and learning analytics. Importantly, cyberlearning projects have also given research teams opportunities to deeply consider and thoughtfully design for equity, a central and enduring challenge for all learning research. Collectively, cyberlearning projects have offered learning scientists, computer scientists, and other researchers new opportunities to join forces to deeply investigate the future of learning with technology without fewer constraints than in the much more common research programs that aim at near-term school improvement.

Cyberlearning research is also establishing a track record of contributions to theory, policy, and practice. For example, cyberlearning was featured in the National Educational Technology Plan, the flagship educational technology policy document for the United States (Office of Educational Technology, 2017). Cyberlearning research was featured at a White House event in 2016, and in high-visibility publications such as the Innovating Pedagogy report. Finally, cyberlearning research is directly touching the lives of hundreds of thousands of students and teachers via the existing portfolio of projects.

Below, we describe directions for further evolution toward broader impact. The first four highlighted directions are also among the NSF Big Ideas (National Science Foundation, 2016), ideas that outline aspects of NSF's long-term agenda.

New Interactions for Learning: Exploring Human-Computing Frontiers

Technological innovations transform what humans are able to do. Human-computing interaction research, in general, is now moving beyond the scenarios of one person and one device. HCI research now considers how diverse groups of people interact with ensembles of different devices. Further, research is moving from a focus on simple transactions to understanding how technology can support more extended problem-solving scenarios, including scenarios where people will be learning with computer-based agents as they work on complex challenges.

Cyberlearning investigates human-computing frontiers by testing new technologies in complex social and pedagogical configurations. Innovations continually challenge boundaries between what people do and what machines do — and not always in ways that are beneficial. Cyberlearning research is investigating these boundaries through its view of learning as a necessary consideration in the design of complex new technological systems, as well as its view of people as social, playful, and constructive. The expressive construction section provides examples of new scenarios — for example, when students become involved in making their own wearable devices by sewing Arduino computers into fabrics. In the section on classrooms as digital performance spaces, students interact with information displays as they move around; in such spaces, interaction becomes a kinesthetic and immersive experience. Cyberlearning researchers are not only investigating existing human-computing frontiers, but they are designing new ones that creating digitally enhanced experiences that reflect how people learn.

New Analytics for Learning: Harnessing Big Data

An overarching scientific goal in the next decade is to improve the U.S. research data infrastructure by developing new ways of analyzing big data and preparing the next generation of data scientists. How can researchers enhance large-scale data collection, mining, analysis, and visualization to enable the research community and the general population to ask and answer important questions?

Cyberlearning has already played a key role in advancing research with large, diverse data sets. Large-scale projects like Cities of Learning are providing insights into what is needed to create cross-context, multisource data collection infrastructures with a goal of helping communities generate information that is useful to its members. Sensors and eye-tracking technologies used in multimodal data analysis mean that direct measures of human emotion and interest can be used as data sources to drive decision making, rather than proximate forms of data such as survey responses that were meant to represent them. By exploring uses and sources of big data through a learning sciences lens, cyberlearning researchers can offer insights into how those data can enhance human potential.

Further, a highly educated workforce matters. Developing a highly educated workforce will require better understanding of how to use big data to shape effective learning trajectories that fit a diverse population. Therefore, cyberlearning researchers have an opportunity for profound impact by engaging in research with big data that helps shape large-scale solutions to workforce challenges.

New Strategies for Inclusive Learning

NSF has long collected and shared national indicators that point to the profound need to broaden participation of underrepresented groups in STEM learning. More recently NSF made a major investment in building capacity called Inclusion across the Nation of Communities of Learners of Underrepresented Discoverers in Engineering and Science (INCLUDES). INCLUDES supports collaborative partnerships of local, state, and federal agencies, higher education institutions, industries, and nonprofit organizations to design systematic approaches to ensure underserved communities have equitable exposure to high-quality STEM learning experiences. Importantly, the program challenges partnerships to engage in new “collective impact” and “networked improvement community” approaches to work together to drive continuous improvement (Bryk, Gomez, & Grunow, 2011).

The cyberlearning community’s commitment to equity of educational opportunity and focus on design and formative research make cyberlearning a natural partner for ensuring the success of INCLUDES. An obvious way cyberlearning researchers can assist INCLUDES is by sharing what they have learned about how innovative technologies have helped young people in high-poverty neighborhoods. For example, cyberlearning research is developing tools to map learning opportunities in neighborhoods and helping citizens to advocate for their learning needs. Projects such as Cities of Learning and Mobile City Science study how to give young people a voice in their own education. More broadly, the cyberlearning community’s persistent interest in providing alternative ways of interacting with STEM — whether through remote labs, makerspaces, or virtual tutors — is expanding educational opportunities for those with physical and cognitive disabilities, for those in rural or low-resource locations, and for those who are not successful in traditional classroom settings.

New Teamwork in Learning Research: Convergent Science

The challenges of understanding and fostering learning in a complex technological society can no longer be effectively tackled within a single scientific discipline, such as psychology or neuroscience. Computer scientists, in particular, want to engage in building new knowledge about how people learn, as do engineers, data scientists, economists, and those in many other scientific professions. The commitments of the cyberlearning community are to the future, to design, to communities, to equity, and to empowering the learner. These commitments direct attention to problems that do not fit any single scientific discipline. Progress in research will be the strongest when scientists come together to conceptualize the research questions, determine how to integrate data collection to enable overlapping analytic frameworks, and envision implications and innovations together. The existing cyberlearning projects already show that convergent research can be productive: Most projects have already succeeded in integrating two or more disciplines. Hence, cyberlearning has a potential for broad scientific impact by providing an ideal context to nurture convergent science.

One area that demands convergent science is the challenge of support learning in communities. Traditionally, most research on learning has focused on learning in both in-school and out-of-school settings, but learning in communities at large is less commonly a subject for innovation and investigation. The advent of smart and connected communities — places where technologies inform and inspire inhabitants to take action to improve their regional setting — is leading to important new studies and shaping how learning takes place outside institutions. Buiding success smart and connected communities will require engineers, computer scientists, sociologists, learning scientists, community advocates and many others to bring their knowledge and insights together. The mapping-based designs discussed in this report offer one glimpse into how cyberlearning may infuse smart and connected communities with new learning opportunities. An innovation workshop hosted by CIRCL explored this topic in greater depth (Fusco, Remold, Roschelle, & Schank, 2016). Community-based learning has powerful potential, yet convergent science will be necessary to make it a reality.

Next Steps

The purpose of this report is to communicate what cyberlearning is, to share examples of designs and methods that illustrate what is being accomplished, to contextualize these accomplishments as part of a larger portfolio, and to suggest how yet greater impacts may be realized.

There is much work to do. Designing the future of learning is not simple. As the cyberlearning field grows and evolves, it is essential to engage in community reflection on where we have been, where we are, and where we want to go. The present crop of cyberlearning projects is already transforming the way people understand how, where, and when learning takes place and how researchers can investigate those experiences. In contemplating next steps, it will be important to think about how our community can enhance its impact on learners and educators by joining forces with others in such areas as the Frontiers of Human Computer Interaction, Harnessing Big Data, Inclusive Learning and Convergent Science. Our community's strong commitments to equity, innovation, multidisciplinarity, and designing for the future put us in a strong position to provide unique perspectives that will strengthen NSF's Big Ideas and other national and international education initiatives.

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