Unveiling the Value of Exploration: Insights from NSF-Funded Research on Emerging Technologies for Teaching and Learning

By the Center for Integrative Research in Computing and Learning Sciences (CIRCLS)

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Authors

Camille Ferguson, Judi Fusco, Shari Gardner, Kip Glazer, Sarah Hampton, Cassandra Kelley, Aditi Mallavarapu, Wendy Martin, Sophia Ouyang, Sarita Pillai, Yenda Prado, Zak Risha, Jeremy Roschelle, Erin Walker.

Interviewees

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Executive Summary

What results from exploratory, interdisciplinary research on innovative uses of technology for teaching and learning? Classic exploratory research looks for patterns in data—or pilots a tentative design for a later large-scale summative study. Such research can be valuable, yet it is limited in scope; the focus either on refining or confirming a hypothesis. Rarely does this research result in the discovery of new ways in which rapidly changing technologies like AI could best be used by students and teachers in the future.

The National Science Foundation (NSF)'s mission focuses on research driven by curiosity and discovery. The future of teaching and learning is one nationally important topic of curiosity and discovery, especially as new and emerging technologies, such as artificial intelligence (AI), are now rapidly permeating educational settings at all levels: preK-12, postsecondary and workforce learning. One NSF portfolio of research has provided funding to interdisciplinary teams of scientists who are curious about these technologies and seek to discover how to best use technology to advance teaching and learning. The intent of this portfolio has been to stimulate highly creative, context-driven approaches to strengthening learning for diverse students of all ages across topics that include science, technology, engineering and mathematics (STEM).

At the request of NSF, the Center for Integrative Research in Computing and Learning Sciences (CIRCLS) analyzed this portfolio, seeking to understand the value of interdisciplinary, exploratory research. CIRCLS both examined the characteristics of the overall portfolio and interviewed principal investigators (PIs) funded by the NSF. We found that this form of research enabled PIs to ask new questions, combine different kinds of expertise, engage collaboratively with practitioners, and design equitable technology-enhanced learning experiences. This report provides details and offers recommendations for the future of the field of interdisciplinary, exploratory research.

About the NSF Exploratory Programs (EXPs)

In this report, we'll frequently refer to three related NSF programs: Cyberlearning, Research on Emerging Technologies for Teaching and Learning (RETTL), and Research on Innovative Technologies for Enhanced Learning (RITEL). For convenience, we will hereafter refer to these programs as the NSF Exploratory Programs (NSF EXPs) because they all emphasize exploratory, interdisciplinary research on the future of learning with technology. Between 2017 and mid-2024, NSF EXPs funded 208 projects in 32 states across the country. Each project was funded for about three years of initial discovery work on a future-oriented use of technology to improve teaching and learning. The work in this portfolio makes it possible to better understand the value of small-scale exploratory projects within the larger science enterprise.

History of the CIRCLS Community

One particular strength of this NSF EXP portfolio is that it has a history and a community. The community is an interdisciplinary group of learning and computer scientists who are interested in designing and conducting research around innovative learning experiences. This community has been supported for many years by the NSF-funded Center for Innovative Research in Cyberlearning (CIRCL), which later became the Center for Integrative Research in Computing and Learning Sciences (CIRCLS).

To provide context, in 2017, several things changed simultaneously. First, NSF decided to focus the grants for this type of work ***only*** on modest-scale ($1 million or less), exploratory projects that were required to be interdisciplinary. Second, the nature of emerging technologies for education began to shift, with new forms of artificial intelligence becoming available to educational designers for "ambitious mashups" with other educational technologies and ideas. Third, a pandemic hit, shifting the relationship between technology and education. The time period from 2017 to the present has been particularly interesting for examining the role of exploratory research—for example, when a pandemic hits, exploratory research can more rapidly pivot.

Through a range of events, resources and learning opportunities designed to be collaborative and inclusive of practitioners and researchers, CIRCLS has helped the community grow into one that embraces equity, accessibility, and innovation. Over the years CIRCLS has produced reports on topics of interest within NSF and this research community. This report is the latest in a series of reports about the CIRCLS community, each of which investigates the ways exploratory projects contribute to NSF's mission of building scientific knowledge and translating research into practice. This report focuses on the character and contributions of exploratory research, as seen through analysis of the portfolio and stories of the investigators who did the work.

Portfolio Analyses

CIRCLS conducts many kinds of analyses of the NSF EXP portfolio. Our analyses have explored how trends in topics have evolved over time, the kinds of expertise PIs and co-PIs have, and social networks among interdisciplinary project team members. For this report, we focused on two questions to help identify PIs for interviews: What topics have been consistently emphasized in the portfolio, and which have received more emphasis most recently? Based on our review of the various portfolio analyses we selected these key topics for this report: Artificial Intelligence (AI), Virtual and Augmented Reality, Collaborative Learning, Accessibility and Learning, and Simulations.

Additionally, we asked: Is there evidence that exploratory projects funded by NSF EXPs are achieving the level of innovation they were designed to achieve? To answer this question, a new preliminary analysis of the portfolio looked at the publications generated by nearly 100 of the funded projects since 2017 to see whether they were more novel than publications in the same database (OpenAlex). Early findings indicated that the publications from projects funded through NSF EXPs had more novel topic pairings than a random sample of publications from the database.

Understanding the Character of Innovative Interdisciplinary Exploratory Research

To explore the nature, value, and impact of engaging in innovative interdisciplinary, exploratory research projects through NSF EXPs, we interviewed PIs, asking what was most valuable about having the opportunity to do exploratory work and what lessons they learned from engaging in this form of research. We then conducted a thematic analysis of the PIs' responses. Several key ideas emerged:

Exploration and Discovery Across New Frontiers

- Exploratory research created a space for innovative projects in underappreciated and understudied spaces.
- Engaging with data in more open-ended research gave PIs the flexibility to focus on unanswered, novel, and reframed investigations to develop something new.
- The NSF EXP portfolio led to substantive collaborations across disciplines to advance teaching and learning.
- Engaging in exploratory research provided the freedom to re-imagine the future for less-often researched technologies that could have educational applications.

Equitable Co-Designed Learning and Practice

- Researchers used exploratory approaches to seek input from underrepresented voices.
- In particular, researchers employed "co-design" to envision possible futures from the perspectives of researchers, partners, practitioners and youth, and this led to changes of direction in the research and new discoveries.
- To develop equitable emerging technologies for learning, researchers focused on learner variability and user-directed customization.
- Practitioner expertise was important throughout the research process, not just while defining the problem.

Emerging Impact Through Networked Communities

- PIs could not fully anticipate the future impacts of their exploratory work; however, successful transformation of initial ideas to better serve educational needs was seen as an important marker of progress.
- Participation in networked communities such as CIRCLS added capacity to research teams and supported practitioners' growth by tapping into a national expert group with diverse interdisciplinary knowledge and perspectives.
- Researchers who conduct exploratory projects that don't fit established research trajectories faced barriers to disseminating novel or unprecedented research findings.
- Feedback from a networked community that included practitioners as well as researchers on the utility of emerging technologies in learning environments increased the impact and reach of exploratory research.

Recommendations

Based on this thematic analysis, we make the following recommendations:

1. Create consistent opportunities for the field to engage in future-oriented, exploratory research across directorates and programs in directorates.
2. Intentionally nurture interdisciplinary research identities and researcher-practitioner partnerships.
3. Continue to uncover processes, methods, and flows that are uniquely important in exploratory, interdisciplinary research.
4. Support coordination networks composed of researchers and practitioners to grow the field, synthesize outcomes, and amplify broader impacts.

Introduction

New and emerging technologies, such as artificial intelligence (AI), are now rapidly permeating educational settings at all levels, including preK-12, postsecondary and workforce learning. More than ever, research on learning technologies is needed to provide necessary knowledge for guiding use of these technologies to advance teaching and learning, with attention to broadening participation in science, technology, engineering and mathematics (STEM).

In this report, we develop insights from the portfolios of the National Sciences Foundation (NSF) exploratory research programs: Cyberlearning, Research on Emerging Technologies for Teaching and Learning (RETTL) and Research on Innovative Technologies for Enhanced Learning (RITEL). For convenience, we will refer to these programs as NSF EXPs throughout. The focus of the report is to understand the value of interdisciplinary, exploratory research on these pressing topics.

Specifically, we examine the nature of exploratory research since 2017—a time period during which AI increased in prominence alongside other emerging technologies, including augmented/virtual reality, advanced simulations, new forms of adaptivity, and more. The portfolios were also highly focused on collaborations among computer and learning scientists, often working together with other areas of specialization (e.g., experts in STEM or other topics, in particular settings, and in design for equity).

The NSF portfolios stretch back further in time; for example, the Cyberlearning program started in 2010. Yet beginning in 2017, NSF's solicitations for field-initiated research in these programs became highly focused on interdisciplinary, exploratory research. Now the researchers who received exploratory awards have had time to complete their investigations. Thus, it is a good time to ask:

- What questions, insights, and findings emerge when a research portfolio focuses intensively on exploratory research?
- What is the character of innovative, interdisciplinary, exploratory research?
- What does the field need in order to provide the knowledge required to guide effective use of emerging technology to increase learning and broaden participation?

Our team, based at the Center for Integrative Research in Computing and Learning Sciences (CIRCLS) has served as the community hub for research in NSF EXPs. We've had the role of mapping and analyzing the interdisciplinary, exploratory work conducted by many independent research teams. In this report, we serve this burgeoning research community by clarifying the nature of its work and highlighting the breadth and depth of the research.

By developing an understanding that rises above each individual project, we seek to inspire researchers in the community to hone its work going forward. We also aim to serve funders, both at NSF and elsewhere, who are thinking about why and how to fund interdisciplinary, exploratory research. Further, our CIRCLS team saw the need to cultivate the involvement of educators and emerging scholars engaged in innovative, interdisciplinary, exploratory research. We want to broaden the audiences by increasing understanding of both the knowledge that is emerging from this research and why educator and emerging scholar participation in exploratory research matters.

History of the CIRCLS Community

For more than a decade, the NSF has promoted the development of an interdisciplinary research community—bringing together learning scientists and computer scientists to explore how emerging technologies can be integrated into educational settings to enhance learning. In 2017, NSF changed the program structure so that, rather than funding a range of project types, the NSF EXPs only funded exploratory projects. Researchers in this community are allowed the creativity to come up with novel ideas, the flexibility to adapt or change course when necessary, and the courage to proudly share what they learned from failure as well as success.

The NSF EXPs encourage high-risk/high-reward exploratory research because NSF recognizes that pushing at the boundaries of what's possible in STEM education, grounded in what we know about how people learn, leads to innovative learning designs that move the field forward. Funded projects bring together investigators and partners from diverse backgrounds and areas of expertise, sometimes working in unconventional settings, often testing new approaches to learning, and usually employing cutting-edge technologies. NSF EXPs have ranged from investigating how to enable social learning with the use of virtual agents in augmented reality settings to employing AI to help high school engineering teachers assess students' design work (see Portfolio Analysis).

NSF's novel funding structure required new ways of providing guidance, resources and opportunities to the community. Since 2020, the Center for Integrative Research in Computing and Learning Sciences (CIRCLS) has provided that support. The center's mission is to work with NSF EXP PIs, support the needs of the broader research community engaged in exploratory research on emerging technologies for learning, and amplify the resulting insights to broad audiences. Appreciating the unique qualities of this community, the CIRCLS resource center highlights the interdisciplinary, exploratory research that NSF EXP PIs engage in and provides researchers not yet funded through the program with community resources and opportunities. Examples include convenings, expertise exchanges, rapid community reports, and community reports.

Convenings

Every other year, CIRCLS hosts meetings, or convenings, for project PIs, project partners and others who do related work in emerging technologies for teaching and learning. CIRCLS has a long history of exploring diversity in learning, starting with the convening "Designing for Deeper, Broader, and More Equitable Learning," and continuing with "Exploring

Contradictions in Achieving Equitable Futures." CIRCLS has continued these convenings with the themes "Remake Broadening" in 2021 and "Shaping AI and Emerging Technologies to Empower Learning Communities" in 2023. Throughout our work, diversity, equity, and inclusion have been powerful fundamental principles in learning and education to support the learning of more groups.

These convenings are designed to be highly interactive, connecting people from multiple disciplines and with varying kinds and levels of experience. CIRCLS invites speakers who often offer a critical perspective on the technologies the community studies, and structures discussion around the latest findings, the practical realities, and the ethical implications of interdisciplinary, exploratory research. CIRCLS has also invited doctoral students, Einstein Fellows, and classroom teachers to attend the convenings to encourage their understanding of cutting-edge learning technologies, tools, or innovative research projects. Convening participants are encouraged to co-create the community with their colleagues through working sessions. The CIRCLS'21 Convening Outcomes Report reflects the collaborative work we engaged in with the community at a virtual convening.

Expertise Exchanges

Another way the CIRCLS community is supported to engage in interdisciplinary, exploratory research is through Expertise Exchanges. These are virtual working groups that bring diverse professionals together in conversation about learning with innovative technologies. These groups have evolved over time, work together to produce collaborative dissemination products, and have established offshoot groups that focus on activities they identify as relevant. The Expertise Exchanges hosted by CIRCLS include:

- Educator CIRCLS: This group is composed of educators interested in sharing their experiences implementing innovative learning technologies or learning more about emerging technologies for teaching and learning to help bridge the gap between research and practice. This group has a blog, and members of the group have created an Emerging Technology Adoption Framework for preK-12 Education as well as a glossary of AI terms. Every summer, the group also creates webinars where they share more about the work and thinking of the community to broaden the number of educators thinking about the work.
- Emerging Scholars CIRCLS: This is a community that brings together graduate students, postdocs, and other early career scholars who do interdisciplinary computer science and learning sciences research or who are interested in doing this kind of research. This group held a series of mentoring sessions with established scholars in the field, held professional development sessions on topics such as how to make the most of conferences and how to write proposals, and created affinity groups around AI and education, research methods and theory, and educational technology.
- AI CIRCLS: This expertise exchange is open to anyone in the CIRCLS community who is interested in AI and how it intersects with various topics. For example, the group

held a series around community partnerships and a project incubator series on literacy and AI, held a session on AI and Education Policy, and ran mock review panels to help broaden participation in NSF programs and offer professional development to the next generation of principal investigators. In addition, six emerging scholars were invited to collaborate with the Journal of Computing in Higher Education (JCHE) on a special issue on AI and education equity in higher education.

Rapid Community Reports

Rapid Community Reports were created to provide this exploratory research community the opportunity to share about ongoing work more quickly than is typical with standard academic publications. There are three types of RCRs researchers use to share ideas to build knowledge in the community: primers (introductions of key topics in learning science and technology), workshop outcomes (results from focused meetings on themes), and design reflections (critical analyses of emerging designs).

Community Reports

This current report on interdisciplinary, exploratory research is the fourth in a series that explores and reflects on the work of the community of researchers who investigate emerging technologies for teaching and learning. In 2017, the Center for Innovative Research in Cyberlearning (CIRCL) resource center published Cyberlearning Community Report: The State of Cyberlearning and the Future of Learning With Technology, which presented a variety of projects that represented key genres or categories of research that characterized the field of emerging technologies for learning at that time, such as Community Mapping, Expressive Construction, and Virtual Peers and Coaches, as well as research methods such as Multimodal Analysis and Data Analytics for Assessment.

In 2020, the CIRCL team worked with a group of experts in the field to reflect on eight years of projects funded through NSF's Cyberlearning programs. The report, titled Ambitious Mashups: Reflections on a Decade of Cyberlearning Research notes that many of these projects creatively integrate various ideas and topics, such as AI, collaboration, equity, or informal environments, in ways that push the frontiers of teaching and learning.

Last fall, in 2023, the CIRCLS team published Partnerships for Change: Transforming Research on Emergent Learning Technologies. The report shares the experiences of researchers working in partnership with teachers, administrators, informal educators, community organizations, neurodivergent youth, community college faculty, tribal nations, and institutional review boards to co-create mutually beneficial research experience with emerging technologies for teaching and learning.

Figure 1: Covers of community reports published in 2017, 2020, and 2023

A consistent storyline connects these reports. Following a first report that benchmarked the state of the field, a second report uncovered a key characteristic of the most exciting exploratory projects—that they combined and integrated multiple technologies to explore powerful new designs for learning. A third report revealed that partnerships are at the center of innovative exploratory design work, driving creative change. Now, this final report in the series looks retrospectively at the portfolio through the eyes of the PIs: What was truly new and different about how PIs in this portfolio conducted exploratory, interdisciplinary research?

Portfolio Analysis

Overview and Methods

CIRCLS regularly reviews and analyzes the NSF EXPs portfolio, as well as NSF's emerging learning technology portfolio, more broadly. This is done to increase our understanding of the research topics being addressed by this community, as well as to help NSF understand whether this exploratory research is pushing the envelope forward and achieving the intended level of interdisciplinarity and innovation. We use a wide range of approaches, from more traditional methods, such as analyzing survey data using descriptive statistics, to more innovative methods, including machine learning algorithms. These approaches allow us to uncover emerging and interesting trends across exploratory learning technology projects. This includes trends related to the topics addressed by projects, as well as trends in partnerships, interdisciplinarity, and the demographics of the researchers and other members of the CIRCLS community. Analyses also allow us to examine how trends have evolved over time and which project topics are consistently the focus of exploratory projects in this portfolio.

In order to identify focal topics and PI interviewees for this report, we drew on findings from prior reviews and analyses of the portfolio with a goal of identifying exploratory research topics that met at least one of the following criteria: 1) common/prominent across the portfolio, 2) trending or popular, 3) long-term trajectory/evolved across many years, 4) an

NSF priority, 5) emergent/up and coming in the portfolio that we believe will become more prominent in the next 5-10 years).

Multiple data sources and analysis methods have been used to understand the breadth and depth of exploratory learning technology research, including:

- Data Sources:
  - PI surveys
  - Human coding of expertise from professional websites and online CVs
  - Project information pages
  - Publication datasets
- Methods:
  - Identifying: Use of machine learning algorithms to identify projects funded by NSF programs beyond the NSF EXPs that were thematically similar to NSF EXPs projects and should be included in the CIRCLS community
  - Tagging: Natural language processing to "tag" project abstracts
  - Mapping: Visualizations to map the expertise of researchers in the community
  - Analyzing:
    - Quantitative/longitudinal analysis of survey data
    - Social network analysis to reveal patterns of (1) diversity of expertise and (2) intensity of inter-expertise collaboration within the community
    - Qualitative analysis of project information pages
    - Bibliometric analysis of interdisciplinarity and novelty of project publications

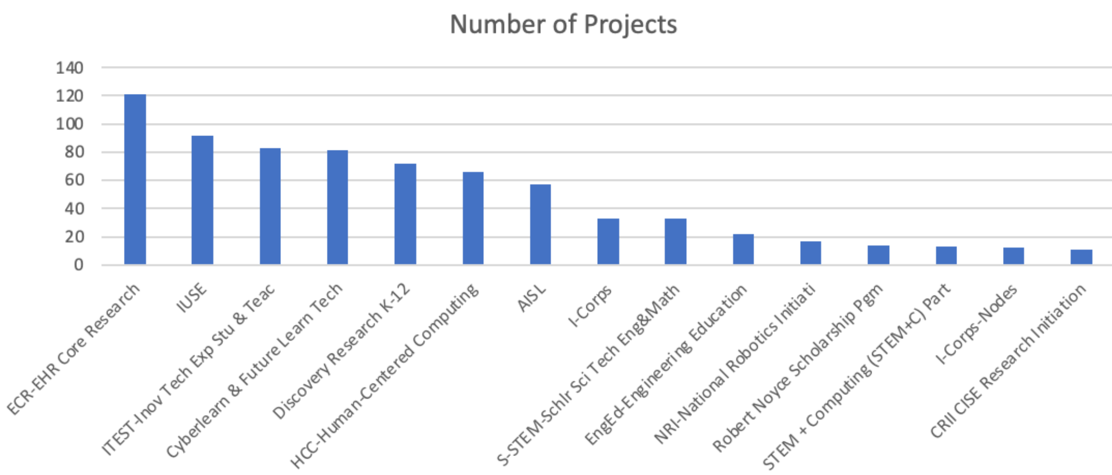
These data sources and methods have led to rich visual representations of the CIRCLS community. For example, the tree map shows the different expertise in our community, the social network analysis shows the kinds of collaborations that bring diverse expertise together (Mallavarapu et al., 2023), and the animated project tag race-chart shows changing trends over time in the research undertaken by the community.

Analysis and Findings

Identifying Relevant "Beyond NSF EXPs" Emerging Technology Projects

CIRCLS was designed to support researchers funded by NSF EXPs, as well as non-funded researchers doing research in emerging educational technology. To identify relevant NSF projects outside of NSF EXPs, we trained a machine learning classifier on NSF EXPs project abstracts that were labeled with a list of project topics, or "tags," from the CIRCLS PI surveys. We then applied it to projects awarded by other NSF programs across the EDU directorate (see Figure 1). We identified 172 projects funded through NSF programs other than the NSF EXPs between 2017 and 2024 that focused on emergent learning technologies. CIRCLS included researchers from those projects in communications related to CIRCLS resources and future opportunities.

Figure 1

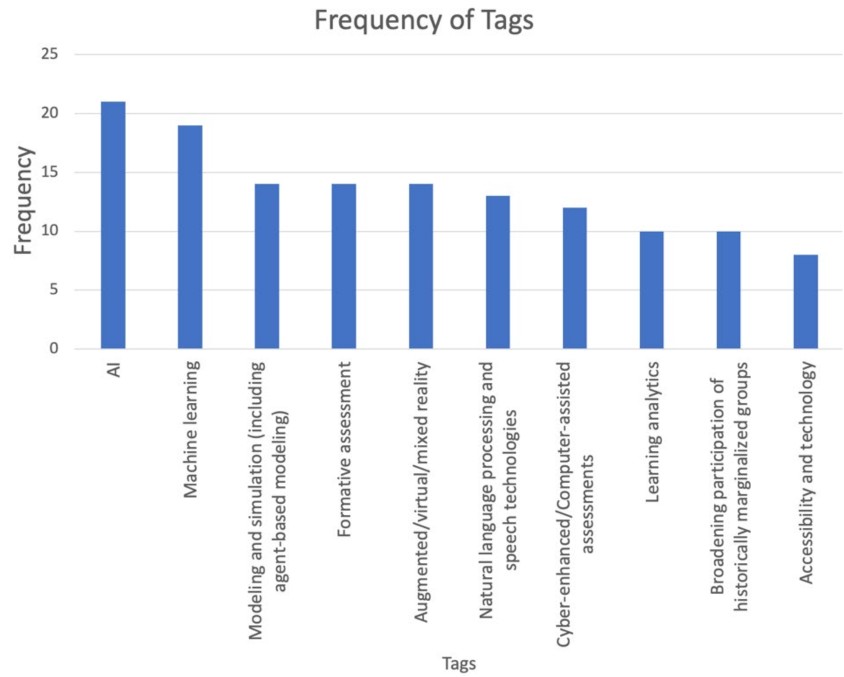


Tagging Projects to Understand the Breadth of Exploratory Research

To understand the extent of the cross-disciplinary research contributions of this community, the CIRCLS team developed a tag-based framework consisting of 49 project tags, hierarchically arranged within 10 major categories of interest. While the tags have been modified over time as new projects and topics have been added to the portfolio, they still provide important insights about the evolution of topic trends in the portfolio, laying the foundation for the analyses presented in the remainder of this section. PI surveys contribute to the majority of data we have on tagged projects. NLP techniques were used to tag projects for which we did not have survey data.

Once all exploratory research projects were tagged, we were able to analyze the data and identify the top 10 tags that emerged (see Figure 2). The most frequently detected tags were ''AI'' (8.5%), ''Machine Learning" (7.7%), ''Modeling and Simulation," "Formative Assessment," and "Augmented/Virtual/Mixed Reality" (all 5.7%). The equity- and social justice-related tags, "Broadening Participation of Historically Marginalized Groups" and "Accessibility and Technology," were also in the top 10.

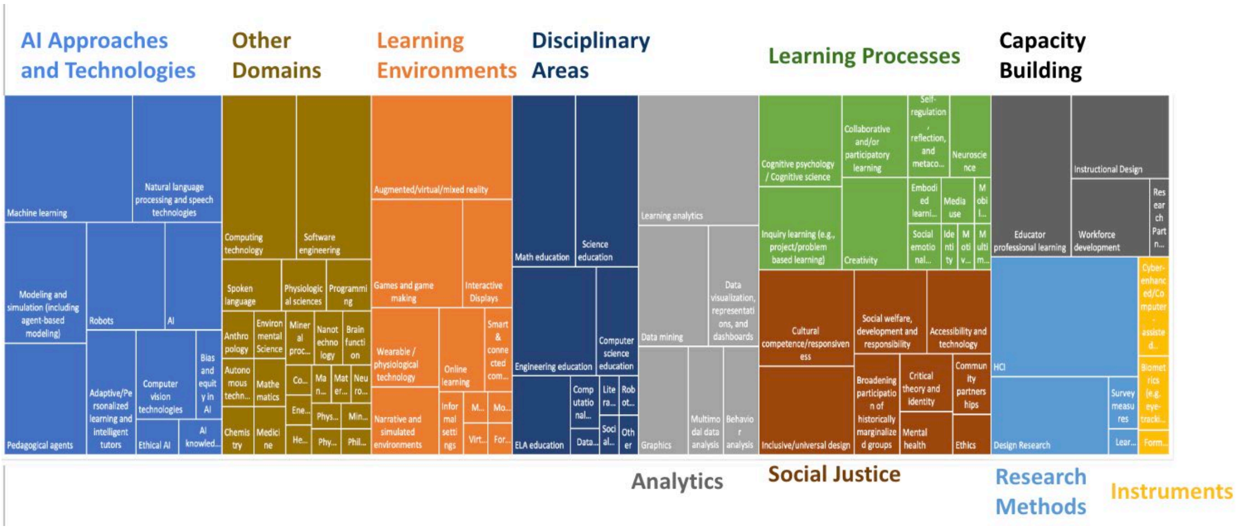
Figure 2: Top 10 tags depicting top research interests in 2022



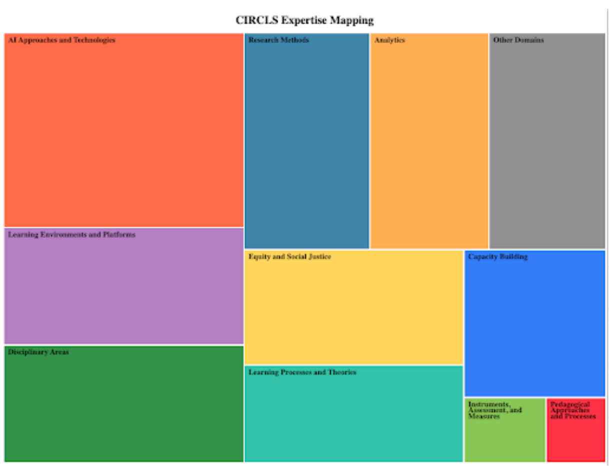
Mapping Community Research Expertise

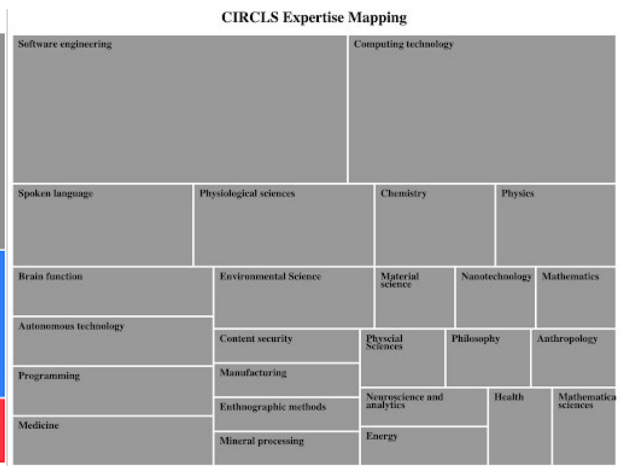
Another area of interest was the interdisciplinary expertise of the researchers engaged in exploratory research, as one goal of NSF EXPs was to bring together interdisciplinary teams at the intersection of technology and learning sciences research. We manually cataloged research expertise for 145 researchers (awarded under RETTL in the year 2022-2023), visiting their websites and CVs. Using these data we created a tree map visualization of the expertise of the community (see Figure 3). The colors of the tiles represent the high-level categories, which are further divided into smaller tiles or codes that represent fine-grained, specialized, and self-identified expertise of the researchers in the community. The size of the tiles represents the relative number of people identifying that topic as their expertise. As you can see, **AI approaches** account for 20% of the expertise (refer to the orange block in top left corner in Figure 4; dig into the interactive tree map here). Uniquely, due to the nature of the research, this community includes researchers from various domains outside of educational technology research (see the expanded inset of other domains in Figure 5). These include a pool of researchers with expertise in **AR/VR/MR**, and game-based environments. Sub-expertises like ethical AI and broad social justice-related codes were also represented (the yellow box at the center of the visualization). The tree map visualization helped us capture the interdisciplinarity within the community, which extended beyond the prerequisite computing and learning expertise required for the NSF EXP projects awarded under RETTL. The map helped to demonstrate how multidisciplinary project teams are and helped guide our selection of topics for this report.

Figure 3: NSF EXP expertise for projects awarded under RETTL based on online websites and CVs



Figures 4 and 5



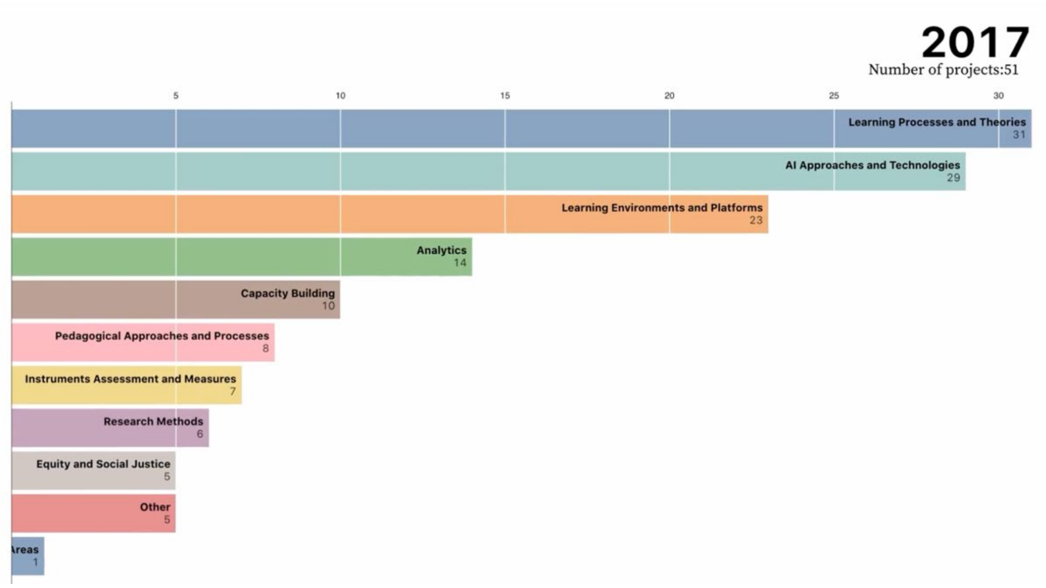


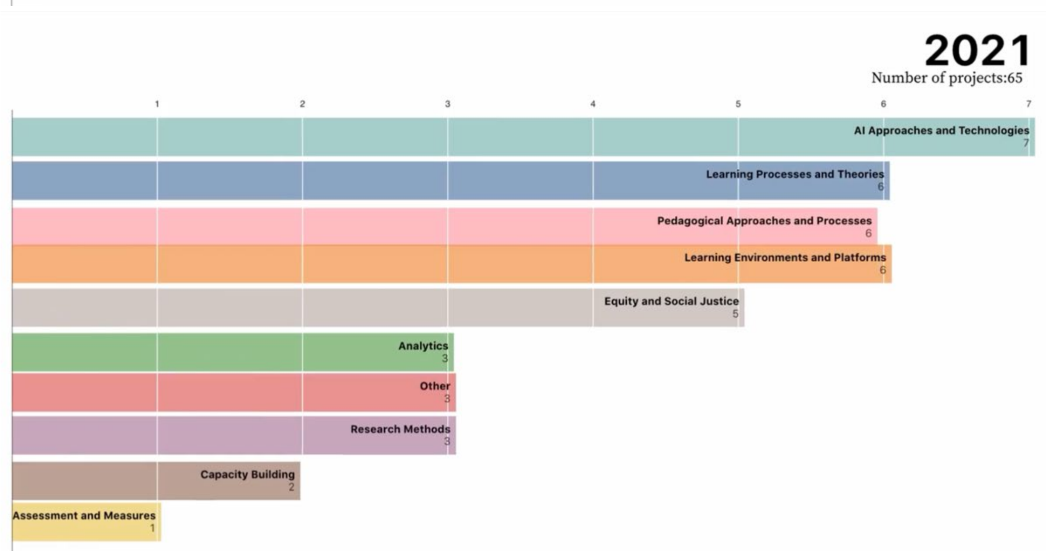
Evolution of Thematic Trends Over Time

Using the above method of detecting relevant keywords in project abstracts, we tagged all NSF EXPs projects awarded between 2017 and 2021, and used them to study the changing trends of research interests (represented by project tags) within the community. We visually represented the number of projects and the top 10 dominant broader categories representing the fine granular tags in a race-chart. The race-chart is an animated version of individual yearly bar charts that depicts the changes in the positions of the bars, showing evolving trends in the research interests among the community.

We identified 10 broad research categories, which include AI approaches, learning environments, learning processes, social justice, and capacity building, among many more. As you can see in Figure 6, in 2017, AI was one of the top topics being addressed by projects, with learning processes and theories taking precedence. But starting in 2018, and inspired by the big push by NSF on AI at the end of 2017, exploratory research became more AI focused. The race-chart also shows that very few projects focused on categories like social justice and equity in 2017, but that over time these topics rose closer to the top (see Figure 7). This trend indicated that the community is interested in creating equity- and social justice-driven technologies for learning, making them important topics to focus on in this report.

Figures 6 and 7



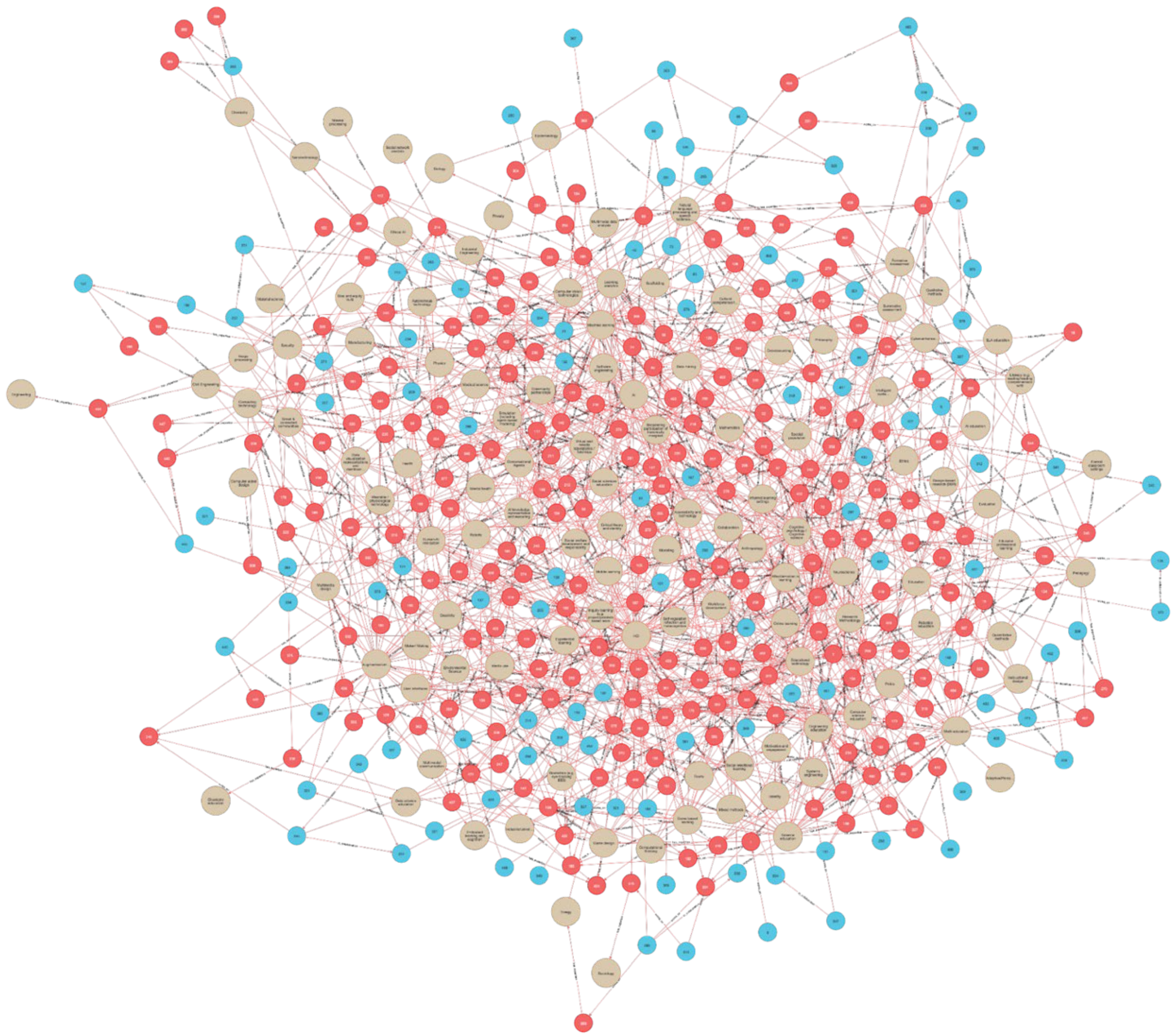


Analyzing Interdisciplinary Research Through Social Network Analysis

To further characterize the research contributions and work of this community, we constructed a social network depicting the project collaborations and conducted an analysis that allowed us to (1) visualize investigator relationships and research collaborations, and (2) map the interdisciplinary contributions. Specifically, we were able to highlight the diversity of expertise within the project teams and the intensity of a research topic across the community.

The network connected the PIs and Co-PIs of NSF projects between 2011 and 2022 to visualize the research community (Figure 8). The project (blue nodes) is connected to the investigators (red nodes) and the topic areas they work on (tan nodes) via the "has expertise" edge (see Figure 8, access the interactive network by Aditi Mallavarapu). This network depicts 238 researchers connected to 87 projects and represents 116 expertise areas that form the "building blocks" for interdisciplinary research in this community.

Figure 8



Drilling down further on the identified patterns of expansive interdisciplinary reach of the community, we used a three-year portfolio of NSF EXP projects awarded under RETTL from 2021 to 2023 to examine the intensity of research topics. We identified "hotspots," or high intensity research topics within the community, which included HCI, AI, cognitive psychology/cognitive science, neuroscience and educational technology, as well as "cold spots," or low intensity areas that we identified as potential "entry points" for integrating knowledge from other domains and experts. Several areas of expertise related to equity and accessibility, including ethical AI, equity in education, working with special populations, and broadening participation for underrepresented communities, were identified as cold spots, with less than two projects through the three years. These cold spot topics were identified as areas of potential growth for the community and informed our decision to focus on accessibility and learning in this report (see Mallavarapu et al., 2023 for more details on the devised metrics).

Project Information Pages: Key Project Outcomes and Innovations

The Project Information Page was developed in collaboration with NSF prior to the CIRCLS'23 convening as a way for NSF EXP project teams to showcase their key findings and technical and learning innovations, with the goal of demonstrating the impact of interdisciplinary, exploratory research projects and the NSF EXPs overall.

We qualitatively analyzed the findings and innovations from the 51 Project Information Pages submitted to CIRCLS by RETTL PIs. The key themes that emerged from this qualitative analysis (listed below) revealed a rich story about the accomplishments and impacts of the projects funded under RETTL, especially related to AI and educators, accessibility, collaborative learning, VR/AR and simulations. These themes informed the key topics of the report, PI selection, and the interview questions we developed for PIs. Through the PI interviews, we were able to dig deeper into not only the accomplishments of these projects but also the lessons and opportunities that arose as a result of the interdisciplinary, exploratory research.

Below we provide a description of major themes we identified through the analysis of the Project Information Pages and their importance. See Appendix A for a high-level table of all themes and associated project examples.

- **Expanding accessibility for learners through digital tools**: Through co-designing with learners with disabilities and leveraging new forms of technology such as AI and AR/VR, CIRCLS projects are pioneering new ways to expand digital accessibility for all learners.
- **Alternative modalities in CS education**: CIRCLS community members are building innovative solutions to combat racial and gender disproportionalities in CS education through alternative modalities such as AI, AR/VR, tangible computing, and interdisciplinary learning.
- **VR/AR tools in STEM education and workforce development**: As the second-most popular CIRCLS project tag, CIRCLS projects are applying VR/AR technology to STEM education and workforce development to replicate hands-on learning in a low-stakes environment.

- **Broadening participation of marginalized groups through technology**: CIRCLS teams are designing tools and programs that challenge existing structures of learning and expand equity in the areas of literacy, social studies, data science, CS, and language learning.
- **Centering educators in AI/ML tools**: With the rapid rise of generative AI in education, CIRCLS researchers are developing tools that center teachers by reducing their time spent on mundane tasks and empowering them to remain at the forefront of decision making and instruction.
- **Co-designing with youths, LLM limitations and successes**: These themes are cross cutting and therefore are discussed within the other themes, rather than separately.

Expanding accessibility for learners through digital tools

NSF EXPs researchers recognize the importance of designing accessible and inclusive digital learning tools for ensuring equity in both digital and physical educational spaces. While the World Health Organization (WHO) estimates that about 16% of the global population lives with a significant disability, over 96% of the most popular webpages are inaccessible to these users (source: WebAIM). A systematic literature review of educational technology developed for learners with disabilities has shown emerging evidence of positive impact on self-confidence and well-being when assistive technology is present (Lynch et al., 2021).

Consistent with the high frequency of AI and mixed realities project tags, several NSF EXPs projects have used these technologies to create tools such as sensory extension devices, virtual/augmented reality games, and executive function interventions to reduce barriers for learners with disabilities. For example, the SAIL 2 project immerses learners in a gamified virtual reality with signing avatars to learn ASL and receive feedback via sign language detection. Led by a team that is majority deaf and uses ASL, the project hopes to bring high-quality ASL education to more deaf children and adults, especially among underrepresented groups.

In addition, some CIRCLS projects are co-designing with learners to better understand their specific needs. NeuroVivid, for instance, is co-designing with a team of diverse neurodivergent teenagers and empowering them to understand their brain and neural activities through constructing their own EEGs. Learners are able to gain technical skills in block coding and circuit building while acquiring the basics of neuroscience to better understand their own brain functionings. The range of innovations and impact from recent CIRCLS projects illustrates the exciting possibilities of digital accessibility beyond just compliance measures; new and cutting-edge technology can transform barriers into opportunities and create meaningful learning experiences for learners with disabilities.

Alternative modalities in CS education

As CS education increasingly becomes mandated across the U.S., over half of U.S. high schools now offer foundational computer science courses. Notably, 2023 has seen the largest growth in high school foundational CS offerings. However, disparities in access to quality CS education persist for Hispanic students, multilingual students, students with disabilities, and economically disadvantaged students based on recent data (Code.org, 2023).

Members of the CIRCLS community are tackling this challenge by researching alternative modalities such as AI, AR/VR, tangible computing, and interdisciplinary learning to offer students opportunities to engage with CS. For example, the Strength Across Schools Research-to-Practice Partnership is co-designing with middle school ELA educators to develop a justice-focused curriculum that integrates computational thinking and computer science principles in ELA. Given that girls and Black and Latinx students often choose not to pursue STEM and CS by fifth grade, the research team seeks to use an interdisciplinary curriculum to provide underrepresented students with more points of entry to CS education.

Some NSF EXPs projects have also focused on supporting collaborative learning, as pair programming has been shown to improve learning outcomes and competency (Hanks, et al., 2011). Pair Programming with Intelligent Social Agents, for example, is developing an AI chatbot for students that can guide them in using pair-programming pedagogy to mimic the experience of coding with another person. This can serve as a low-cost method for under-resourced schools in providing more customized CS learning experiences to students. As demonstrated by these examples, NSF EXPs researchers are building innovative solutions to close the gap in access to quality CS education. Whether it's leveraging AI and mixed realities or partnering with stakeholders, these projects are pioneering new ways for students to pursue CS education and forge their own learning paths.

VR/AR tools in STEM education and workforce development

As the second-most popular CIRCLS project tag, virtual reality (VR) and augmented reality (AR) have seen explosive growth in recent years, especially in the fields of STEM, social sciences, and medicine (Al-Ansi et al., 2023). Within the CIRCLS community, this has translated to widespread application most notably in STEM education and workforce development. A significant number of projects are developing VR/AR tools to better support understanding of STEM concepts ranging from computational thinking in early childhood classrooms to mining engineering courses in postsecondary settings. For example, the GEM-STEP project aims to enhance elementary school students' understanding of complex science topics by providing them the opportunity to create and modify their own embodied models in play-based, mixed-reality environments.

This type of multimodal learning can pique and sustain engagement in STEM learning as well as give students agency in exploring new science concepts. In addition, some projects are utilizing VR/AR for workforce training in high-stakes or high-risk situations that can't be easily replicated, such as medical emergencies and construction safety. Project mTeam is expanding upon their existing multi-user VR platform for cardiac arrest resuscitation to build a debriefing system that captures multimodal data from the VR platform and generates feedback accordingly. This has the potential to improve existing training opportunities for team-based care across other medical settings by drawing on both cognitive and behavioral data from participants. With the wide-ranging application of VR and AR technology, more learners will be able to partake in hands-on experiences that amplify and ground their learning.

Broadening participation of marginalized groups through technology

A recent review of research about the impact of educational technology on students of color suggests that hybrid or blended models of learning may improve academic outcomes, thus highlighting the need for innovative modes of education (Joosten, 2021). In the 2022 CIRCLS intake survey, about 20% of the respondents stated that they are targeting learners from historically marginalized communities and districts serving large proportions of students of color. Several teams are leveraging technology for the empowerment of marginalized groups and expanding equity in the areas of literacy, social studies, data science, CS, and language learning. For example, Transformative Computational Models of Narrative to Support Teaching Indigenous Perspectives in K-12 Classrooms is building computational models of narrative technologies from an Indigenous perspective to sustainably share their knowledge and culture in K-12 settings. Shifting from Western narrative technologies, which are often linear in nature, this project seeks to empower Indigenous community members in creating their own representations and increase the cultural competence of non-Indigenous teachers and students.

Furthermore, NSF EXPs project teams have been intentional about co-designing with underrepresented groups, particularly Black youths, Indigenous communities, and women of color. For example, From Data Literacy to Collective Data Stewardship conducted two years of participatory action research with a youth advisory board to develop a role-based data literacy framework and collaborative data advocacy platform. Through this platform, Black youths from underserved communities will gain critical data literacy on how data impacts their community and take action based on data-driven insights. These examples highlight the growing body of work at the intersection of technology and identity and how technology can facilitate a radical shift in the learning experiences for underrepresented groups.

Centering educators in AI/ML tools

The May '23 report from the Office of Educational Technology asserts that we must "always center educators" and focus on improving educators' quality of work when designing AI tools for education. NSF EXPs researchers are working on a variety of AI/ML tools that utilize generative AI for tasks that are traditionally time and resource intensive (e.g., grading papers, monitoring student work, and providing personalized feedback in real time). For example, the CAREER project, Grasping Understandings of Students Mathematical and Perceptual Strategies Using Real-Time Teacher Orchestration Tools, is developing a set of AI-powered tools that provide teachers with detailed, real-time feedback on student learning and problem solving to support teachers in differentiating math instruction. With the insights generated by AI, teachers still have the agency to interpret and act upon the data.

Continuing on the theme of partnership with educators from the previous CIRCLS report, several teams are in the process of co-designing with teachers to ensure that the final product reflects teachers' most pressing needs. In Exploring Artificial Intelligence-Enhanced Electronic Design Process Logs: Empowering High School Engineering Teachers, researchers interviewed and co-designed with a diverse set of teachers on the impact of AI in their classrooms to develop an AI system that can guide students through the engineering design process. With a research team that consists of former teachers, the project hopes to reduce teacher burdens and expand their capacity of providing timely feedback to engineering students through this tool. As generative AI becomes an inevitable mainstay in our education system, CIRCLS community members will continue to explore ways to enhance learning outcomes while empowering our educators to remain at the forefront of decision making and instruction.

View Appendix A: Themes from Project Information Pages

Bibliographic Analysis: Analyzing Novelty in NSF EXPs

A bibliographic analysis of papers generated from NSF/EXP awards

Purpose

The following work builds upon the analysis of the NSF EXP portfolio by proposing an innovative method using new bibliographic data to explore the novelty of projects. This approach shifts the focus from the initial goals and team composition of projects to the outcomes of these projects by analyzing the papers produced by NSF EXP awards. Our method uses various bibliographic data, such as automated tagged topics of research articles, to provide insights into how awards combined ideas in novel ways and reached various venues. The work also hopes to more broadly demonstrate the role these methods may have in the evaluation and study of research initiatives, programs, and policy.

Publication Dataset

To obtain a dataset of publications, we first conducted a search on the NSF Awards site to find relevant NSF EXP awards. We used two criteria: awards with the Program Element code 8020 and awards with a start date of 2017 or later. At the time of our search, this resulted in 465 awards from the related program, 196 of which with a start date after 2017. As collaborative awards can have multiple entries, we used the unique award titles to arrive at 149 total awards. We then scraped each award page to extract any publications attributed to these awards. This process resulted in 506 unique paper titles from 115 award pages.

Bibliographic Data

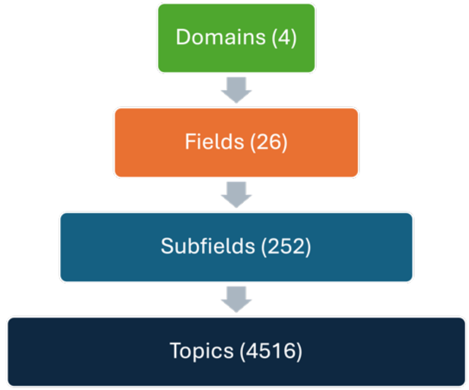
To obtain more information about these publications, we matched them with the OpenAlex (Priem et al., 2022) publication database, which provides bibliographic information such as associated topics, references, publication venue, and other relevant information. Our process successfully matched 443 of the 506 papers from 95 of 115 awards in our dataset. OpenAlex automatically assigns topics to papers using a hierarchical model consisting of four levels: domains, fields, subfields, and topics (Figure 1). Each paper can be tagged with up to three topics, allowing us to examine how papers combined knowledge in novel ways.

Figure 1: OpenAlex's Topic Hierarchy (left) and an Example Topic (right)

Topic Hierarchy

Example Topic

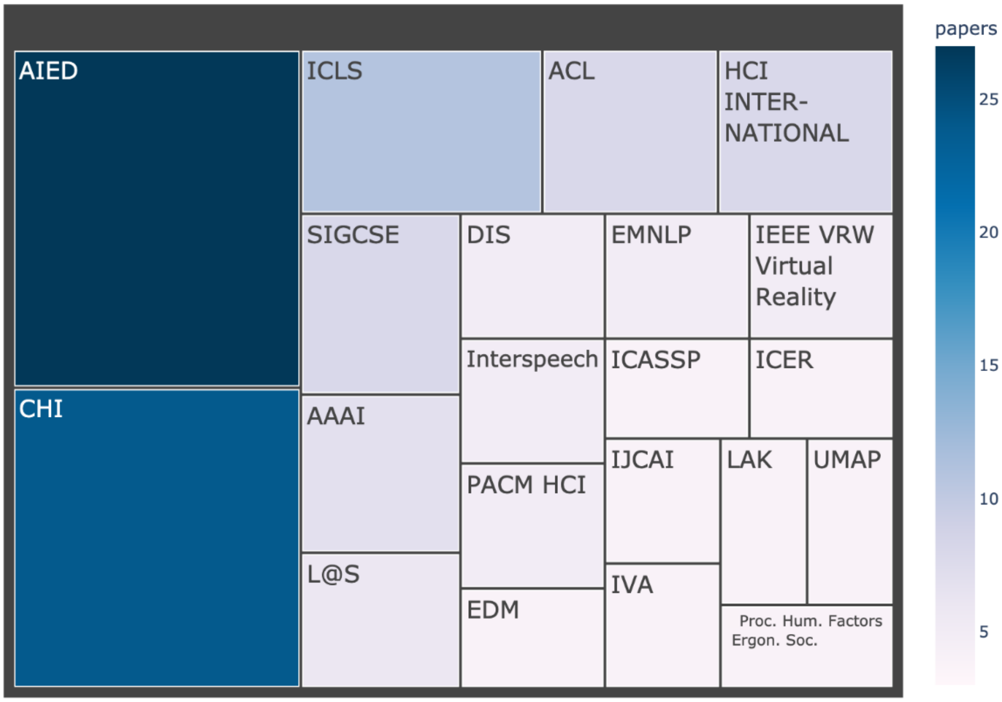
Domain: Physical Sciences
Field: Computer Science
Subfield: Artificial Intelligence
Topic: Effectiveness of Intelligent Tutoring Systems



Most Common Publication Venues

We first sought to get a sense of what publication venues these papers originated from. We used data from OpenAlex and the Semantic Scholar Academic Graph (Kinney et al., 2023) to aggregate the most common venues with five or more papers from our dataset of NSF EXP papers. As indicated in Figure 2, proceedings from the Conference on Artificial Intelligence in Education (AIED) and the Conference on Human Factors in Computing Systems (CHI) were the most common venues for NSF EXP papers.

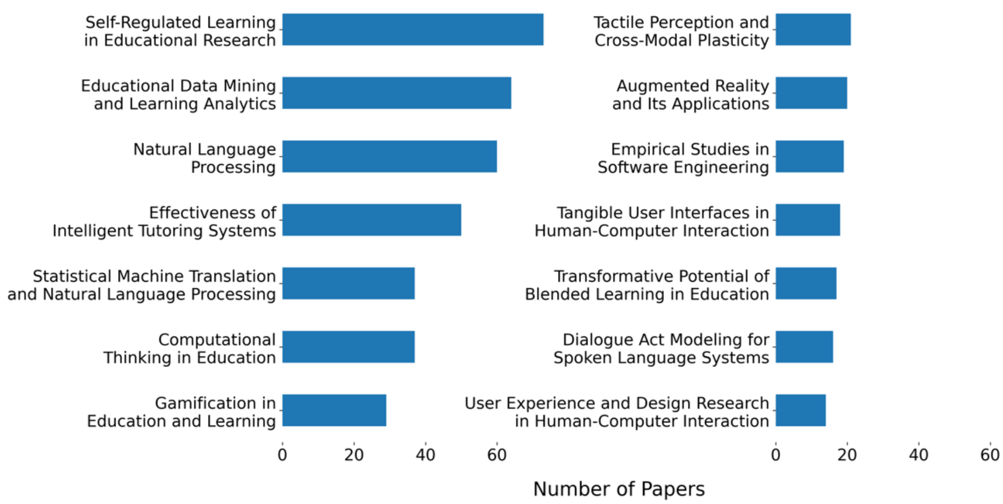
Figure 2: Most Common Venues of NSF EXP Papers



Most Common Topics

Similarly, we also aggregated the most common topics to understand the different types of knowledge represented among these papers. Papers can have multiple associated topics (up to three), and some topics are commonly combined in papers such as *Effectiveness of Intelligent Tutoring Systems* and *Educational Data Mining and Learning Analytics.* Results (Figure 3) helped illustrate the main research areas NSF EXP project papers were contributing to. Likewise, these topics often aligned with prior work of tagging projects and mapping community research interests, further bolstering our confidence in our results. This work collectively helped inform the selection of PI interviewees for the Field-Driven Research Synthesis.

Figure 3: The Most Common Tagged Topics of NSF EXP Papers



Measuring Novelty Through Combinations

Since OpenAlex tags papers with multiple topics, we can analyze how they combine different types of knowledge. Papers with combinations that are rare would be considered more novel as they bring together unconventional ideas. In Figure 4, we provide two examples to illustrate a rare combination of topics versus a common one.

Figure 4: Example of a Rare (left) and Common (right) Topic Combination

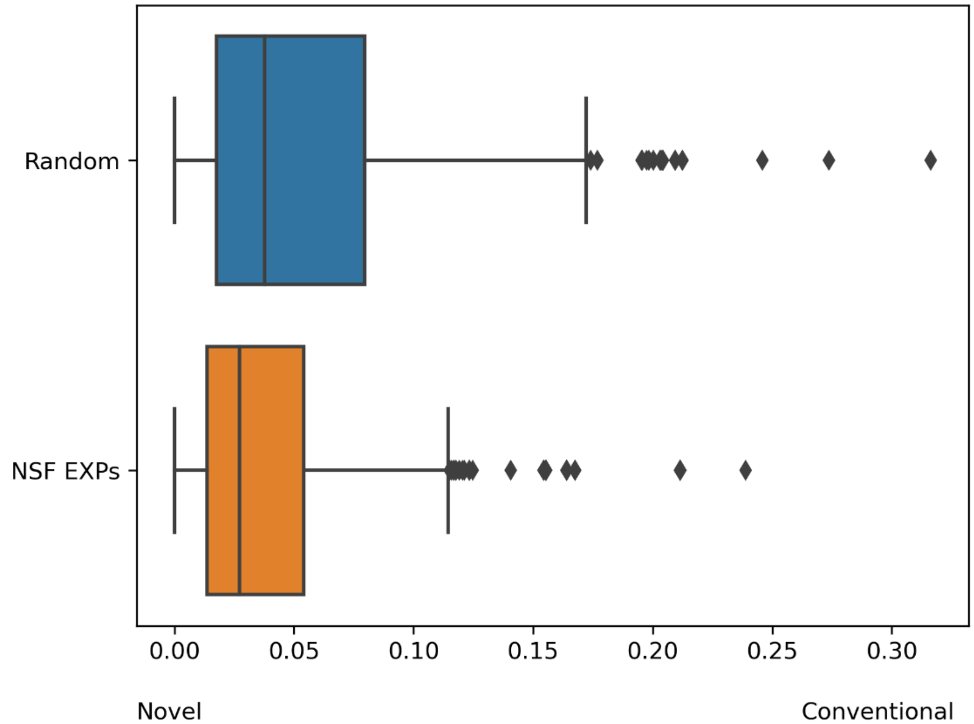
Pilot Analysis of Novelty Bibliometric

To measure novelty, we explore an approach using combinations (Uzzi et al., 2013) similar to that of Leahey and Moody (2014) which compares the likelihood of a pair of topics to appear together in the same paper. For this calculation, we consider all articles in OpenAlex published after 2010, counting how often a paper is tagged with a topic combination relative to the total number of papers tagged with either topic. For each paper, we then identify the rarest topic combination and use it to assign the paper a novelty score.

For a benchmark, we compared the novelty score of papers of NSF EXP papers with a random sample of 1000 articles from OpenAlex. We sampled papers from the same primary fields of the dataset (e.g., computer science, psychology) as well as from the same time period (2017-2024). We then calculated novelty scores for our random sample and compared it with the dataset. There were 5.2% (23) of papers from our dataset and 18.2% (182) of papers from our random sample that were associated with only a single topic. These papers were omitted from our analysis as no novelty score could be calculated. The difference in the number of single topic papers between our dataset and random sample could also suggest NSF EXP papers more frequently cover multiple topics. However, such a result could also be due to other technical factors and limitations related to OpenAlex's process of tagging topics.

While this method is still under development and subject to error, early results of our pilot show promise. We suspected publications deriving from an NSF program that encourages interdisciplinary and exploratory work would tend to have higher novelty scores. This seemed to be the case when comparing the distribution of scores between the random sample and dataset (Figure 5).

Figure 5: Distribution of paper novelty scores



While additional work remains to validate these findings and determine their reliability, they suggest this approach could be suitable for measuring novelty. We plan to investigate limitations of measuring novelty in this manner, including the accuracy of the topic classification and how topics can specifically describe what is novel.

Conclusion

Our methods help demonstrate promising ways to evaluate the performance of awards in the context of novelty and interdisciplinary, exploratory work. Although this research is still underway, it illustrates how combining various streams of data and calculating bibliometrics through topic combinations can quickly yield interesting insights about the output of knowledge and ideas. We believe this work will be useful for understanding the performance and characteristics of interdisciplinary and exploratory programs like NSF EXPs. Such insights could help inform the future direction of research policy and programs.

Field-Driven Research Synthesis: Understanding the Character of Innovative Interdisciplinary Exploratory Research

In December 2023, NSF asked the CIRCLS team to conduct a research synthesis to understand the unique value of interdisciplinary, exploratory research by examining NSF's Cyberlearning and RETTL/RITEL program portfolios (referred to hereafter as NSF EXPs) from 2017 to the present. This synthesis focuses on better understanding what PIs learned from their exploratory projects, including what evolved from that work. Our review of project social networks, PI surveys, keyword maps, project abstracts, and publications informed the selection of PI interviewees across key topics: Artificial Intelligence (AI), Virtual and Augmented Reality, Collaborative Learning, Accessibility and Learning, and Simulations. In June 2024, we completed interviews conducted with 17 PIs across these topics (Appendix B).

Interview Process and Analysis

Each interviewee was selected for their project's contribution to the portfolio, specifically in terms of innovation, interdisciplinarity, equity, and co-designed exploratory research. Initially, we recruited 33 PIs from 30 NSF-funded projects. Of these, 17 PIs from 15 projects (50%) agreed to participate in 60-minute semi-structured interviews.

The interviews aimed to gather PIs' perspectives on the value and impact of engaging in interdisciplinary, exploratory research through NSF EXPs. They explored opportunities, challenges, and lessons learned. Each interviewee was asked the following questions:

1. What was your original project funded through NSF EXPs?
2. What was important about having the opportunity to do interdisciplinary, exploratory research?
3. What were some important challenges and lessons learned from your work?
4. What opportunities arose from your interdisciplinary, exploratory research?
5. What CIRCLS opportunities helped move your work forward?

We analyzed the interviews thematically using first and second cycle coding, directed content analysis, and constant comparative discussion. This approach allowed us to identify, consolidate, and develop insights into the nature and value of innovative interdisciplinary exploratory research across three themes:

1. Exploration and Discovery Across New Frontiers: How CIRCLS PIs investigated emerging technological possibilities by engaging with partners to generate ideas across disciplines

2. Equitable Co-Designed Learning and Practice: How CIRCLS PIs created contextually rich, iterative, learning spaces via co-design and other equity-focused practices
3. Emergent Impact Through Networked Communities: How CIRCLS PIs mobilized networks to support broader impacts through innovation and expansion

Below we elaborate on each theme. Project artifacts and resources are hyperlinked throughout and included in Appendix B.

Exploration and Discovery Across New Frontiers

Engaging with partners to generate ideas across disciplines

Roxanne (AI), Sheryl (Accessibility and Learning), Marjorie (Simulations), and Lorna (Accessibility and Learning)

> *Engaging in exploratory research allowed PIs to convene partners and generate ideas across disciplines by a) fostering collaboration with partners from different fields, b) identifying knowledge gaps, and c) developing ambitious goals and innovative solutions. Below we share specific quotes to illustrate these activities.*

The NSF EXPs specifically called for and supported interdisciplinary approaches to exploratory research. For example, Roxanne described how her AI project, Exploring AI-Enhanced Electronic Design Process Logs, brought technologists, practitioners, and subject matter experts together:

> *I thought it was a really special opportunity in terms of the **collaborations, working across disciplines**, and having a solicitation **that's specifically set up for multidisciplinary and interdisciplinary work**.*

For many of the PIs we interviewed, including Roxanne, the NSF funding afforded opportunities for interdisciplinary engagement. This collaborative engagement across disciplines bridged knowledge gaps, as Sheryl explained in her Accessibility and Learning project, Designing STEM Learning Environments for Individuals with Disabilities:

> *I think it can **provide a foundation to go to the next step.** And I also think it's a type of research where we can get **multiple stakeholders together.** In my experience, you need to take the time to make them comfortable with each other. I consider myself to be **kind of a social engineer**. You start with**, "Well, they don't talk to each other, so we're going to bring them together."***

Sheryl's exploratory project convened partners from diverse disciplines with contrasting perspectives who do not normally engage each other: individuals with disabilities, cyberlearning technology and pedagogy researchers, computing faculty and doctoral students, cyberlearning instructors and designers, leaders of K-12 and postsecondary cyberlearning projects, and IT accessibility experts. This interdisciplinary approach to interdisciplinary, exploratory research helped identify needs and gaps in creating accessible technology in this community and set the stage for future research and development.

Interdisciplinary approaches in exploratory research allow project teams to both identify knowledge gaps that might otherwise have been missed and develop ambitious goals.

Discussing the Simulation project Exploring Social Learning in Collaborative Augmented Reality, Marjorie explains how interdisciplinary collaboration allowed her team to identify and focus on knowledge gaps within emerging technologies research:

> *That's what's so great about NSF work: We're* ***able to identify gaps****. We don't have to solve every research issue right at that moment. We're able to identify gaps and then fill them in as we go forward.*

Finally, collaborating across disciplines supported the development of ambitious goals and arrived at innovative solutions, as Lorna described in her Accessibility and Learning project, Implementing and Testing Signing Avatars & Immersive Learning:

> *Having the opportunity to try to* ***chase those goals that we have, even though they're high****, and even though* ***they require a lot of different areas of expertise that are not always seamlessly integrated****, has allowed us to make a lot of progress with this project. For example, it is not extremely typical that a professor of educational neuroscience like me would have a postdoctoral researcher whose background is solely in computer science and deep learning. So, we are both* ***taking a leap of faith that we can work together across disciplines*** *to make something. And by* ***reaching across disciplines****, we are able to pull together different pieces into one cohesive project.*

Taking a leap of faith and chasing ambitious goals in exploratory research, as Lorna shared, requires engaging interdisciplinary perspectives and expertise.

Exploring emerging technological possibilities

Rebecca and Colleen (Virtual and Augmented Reality), Nikolas (AI), Erin (Collaborative Learning), and Lorna (Accessibility and Learning)

> *Interdisciplinary, exploratory research provided avenues for PIs to explore emerging technological possibilities by a) funding passion projects in understudied and semi-structured spaces, b) affording freedom to explore possible and unimagined futures, and c) enabling research considered high risk or unorthodox.*

Our interviews revealed strong beliefs that engaging in interdisciplinary, exploratory research creates a space for passion projects in underappreciated and understudied spaces, as Rebecca, co-PI with Colleen for the Augmented Reality project Combining Smartphone Light Detection and Ranging with Augmented Reality, explains:

> *This particular project is not through my current affiliation, nor was it through my previous one. This **comes out of my teaching experience** as a high school teacher, and it comes from my husband who is a software developer. This is very much **a passion project**. So, I see exploratory research as a really appropriate place for **passion** projects that can have a lot of impact in **a research space that is underappreciated**, which, you know, is high school physics teaching.*

Engaging with data in semi-structured and unstructured problem spaces also gave PIs the flexibility to focus on unanswered, novel, and reframed research questions compared to more established lines of research. This allowed for speculation and for new ideas to develop, as Colleen commented:

> *I think the exploratory research allows you to know more than just a snapshot at the beginning and a snapshot at the end. **How do things unfold?** We're doing something that's **never been done** in a classroom. **We don't know!** We have maybe a mental model of how we think things are going to play out, **but we don't really know**. You need **a relatively unstructured problem space** in which to develop something new.*

Given the understudied nature of interdisciplinary, exploratory research, it was important to the PIs that NSF funding opportunities not be tied to conventional or established research lineages. For example, during Nikolas's AI project, Supporting Designers in Learning to Co-create with AI, co-creating interactions with AI were in their infancy, and the quality of AI-generated content was not as advanced as it would soon become:

> *The thing that we think was innovative and exploratory was that, at the time, **there weren't a lot of generative AI co-creative interaction**s. There was*

> *some work in the space, but the level of excitement and the functioning of the AI, the actual quality of what was generated, wasn't as good...in many ways it was exploratory to figure out that "if this is coming,* ***we think it's coming soon****."*

> *Rather than "build better AI, make it work better." That's what AI companies are doing. They're great at that. That is not what our group focuses on. We focus on the* ***human interaction*** *side, and we focus in many ways on* ***making the human better****...For example, these agents that help you think through things, these meta-cognitive agents, work. We will make the person better. And every time the AI gets better, hopefully the whole interaction gets better.*

Anticipating the imminent advancements in AI, along with the focus on enhancing human interactions with AI, made Nikolas's work pioneering. As a result, many PIs, including Nikolas, felt that engaging in interdisciplinary, exploratory research provided freedom to envision potential futures beyond the limitations of current technologies.

Erin expressed this sense of expanded imagination and opportunity while discussing the Collaborative Learning project Improving Student Help-Giving with Ubiquitous Collaboration Support Technology:

> *For all of my career up until now, my research has been entirely exploratory, and I see that as the scientific role I am filling. What I am interested in is* ***presenting ideas to people of possible futures****... With the hope of then encouraging people to take [ideas] up in ways that produce more effective learning technologies, but also* ***aspirational technologies****. Technologies that are* ***more agentic in the kinds of agency they enable*** *in learners. Or* ***more empowering, more context sensitive, more responsive****. So presenting* ***a future of what technology could be*** *in contrast to what it is right now...* ***To re-imagine better futures*** *in a way that I don't think you could if you were just doing safer, more incremental, research.*

Erin, like many of our interviewees, was passionate about exploring possible and re-imagined futures—particularly for aspirational technologies in under-researched areas. However, this freedom also presented tensions between embracing the open-ended nature of interdisciplinary, exploratory research and managing the high stakes of developing emerging technologies for learners.

Erin explained:

> *In this space, you have something that is very* ***difficult, potentially impossible, to build. And that's a technical challenge.*** *And then you have this need to deeply understand the educational context, the individual learners, the factors of interest before finalizing a technology design...*

> *There's all these **challenges around negotiating** between the practical needs of whatever context you're in and the scientific needs of the project that's maybe **reaching 5 or 10 years into the future**.*

For some PIs, including Erin, engaging in exploratory approaches presented challenges between balancing freedom and high stakes in ways that were intimately tied to the needs and vulnerabilities of the learner populations that the PIs were trying to serve:

> *So I feel like there's all **these tensions that happen that require negotiation a**s you go from, "I need to deeply understand this" versus "I need to produce something," to "this really needs to work very well in this particular context"—which is a very serious concern especially if you're dealing with members of minoritized groups. A lot of my work has been **very context embedded,** which makes the **stakes very high for something that's also risky** and that has just been this constant challenge.*

Finally, the ability to explore new ideas and possibilities enabled PIs to focus on next-level research of emerging technologies considered to be high risk or unorthodox, as Lorna shared with us:

> *The **NSF took a chance** on us. I don't just say that because I'm reading between the lines, but literally. In 2018, we submitted the first version of this grant proposal, and we received reviews that included comments like **"overly ambitious."** Thankfully we had a very supportive program officer who saw the potential in this work and recommended that we be **funded for an EAGER award**. It's a special mechanism at the NSF that allows program officers to provide partial funding for **particularly high-risk projects**... There was a big question of "**Can it work?** Can we build a high-quality Signing Avatar, put her in a virtual environment, and use her to teach ASL?"... We were able to show that the idea can take off and can work on a **proof-of-concept** level, and then we were able to submit a full proposal in 2020 and receive funding.*

Notably, the program officer recognized the ambitious potential of Lorna's project. At least several lines of underfunded research might not have come to light as NSF EXPs were it not for alternative channels such as EAGER—a funding mechanism that supports high-risk/high-reward interdisciplinary, exploratory research involving radically different approaches and novel interdisciplinary perspectives.

For other PIs, eschewing more established approaches to research—such as large-scale randomized studies using statistical analysis—was critical to the deep exploration of emerging technologies for learning, as Colleen explains:

> *Schools are unfortunately **driven by statistics**. And **the mean does not tell you the whole story**. There's a whole lot of **data that does not sit at the***

mean. *There are a whole lot of students,* ***different kinds of students, who learn in different ways****. And we get to see that, and we get to play with that because* ***we have the flexibility*** *to say, "Okay, well, we thought we were going to use it in this setting, but let's try it in this other setting." And we've been able to do* ***more than we originally planned****.*

Rebecca and Colleen's use of exploratory approaches to analyze data that "does not sit at the mean" was critical to better understanding the impact of student variability and context in their research. Moreover, PIs' focus on developing emerging technologies to support "***different kinds of students, who learn in different ways"*** required engaging in equitable co-design practices, which we discuss below.

Equitable Co-Designed Learning and Practice

Creating contextually rich learning environments

Ross (AI and Robotics), Rebecca and Colleen (Augmented Reality), Lorna (Accessibility and Learning), Brett (Accessibility and Simulations), Ying (Collaborative Learning and AI), and Roxanne (AI)

> *PIs wanted to develop more equitable technologies and experiences for learning. Interdisciplinary, exploratory research allowed them the time to investigate contextually rich learning environments using equitable co-design approaches that a) were context driven, customizable, and took learner variability into account; b) incorporated inclusive approaches and frameworks for teaching and learning; and c) flexibly addressed challenges in co-design.*

Opportunities to investigate contextually rich learning environments aligned with PIs' goals to develop emerging technologies for learning that are context driven and equitable. For Ross's AI and Robotics project, Using AI to Focus Teacher-Student Troubleshooting in Classroom Robotics, this meant discovering that a "one size fits all" approach was not going to work for the diverse users he and his team were aiming to serve:

From the beginning, we intended several different environments, including ***online environments, remote classrooms, inner city public schools, suburban ones****. We intended to* ***find commonalities*** *among these environments that we could design our system around. It turns out* ***not to really work that way****. What we ended up observing was that* ***the ways in which people teach,*** *especially troubleshooting,* ***are very much shaped by the environments in which they are teaching.***

Ross's team learned that developing equitable emerging technologies for learning required addressing user-directed customization and learner variability across diverse learning environments:

> *We would have designed a system that would only have worked in a few places—and it probably would have been the places that didn't need it—had we not* ***looked broadly and with intent*** *to do something helpful. There's a bit of a subtle* ***context shift from looking for the common element that serves everybody to trying to create a system that everybody can use in their own way****. So, one thing we did learn is that* ***the diversity of users has a huge impact*** *on the usage of systems.*

PIs we interviewed pivoted toward the idea that a technology is only as useful as users find it to be; this represented a shift in their thinking of equity-focused design to a more user-centered perspective. In Ross's case, taking an exploratory approach allowed his team to shape technology systems to meet users' needs across diverse learning environments.

PIs used these context- and user-driven design adjustments to customize spaces for teaching and learning. Their approaches included adopting inclusive design frameworks, such as Universal Design for Learning (UDL), to support diverse users, as Rebecca describes below:

> ***When I was a high school teacher****, we would go to amusement parks, go on roller coasters, and collect data. But we only had a few commercial devices, so we started using smartphones. My husband developed a tool that takes all the sensors from smartphones and turns it into useful data. You might think, "why is that even important?" The thing is, if you can plot your data in real time—and* ***you can embody that motion*** *as a physics or a math teacher—****you can now help students understand things*** *like rates and mathematical modeling. You start to l****ay the foundations*** *for things like calculus in a way which is completely* ***hands-on, whole body.***

In Lorna's project, UDL principles were used to support teaching and learning by developing a VR technology to build ASL fluencies with graduated levels of support for deaf individuals and their families:

> *Imagine that you have parents who have a baby that was just identified as deaf. We can imagine that as new parents, they might* ***not have the time or the easy access*** *to arrive at in-person classes on a scheduled timeline. So, they might use resources that are available like YouTube or books.* ***But what if*** *they could learn American sign language from the comfort of their own home using an off-the-shelf VR device* ***at their own pace?*** *And* ***receive feedback*** *while they're learning?* ***Simulating in-person instruction*** *with a deaf signer—that's our use case that drives this work to get more people signing.*

PIs also incorporated UDL principles into their co-design work to support multiple modes of user engagement, as Brett described in the Accessibility and Simulations project Inclusively Designing Sensory Extensions for STEM Inquiry Learning:

> *The simulations themselves are built in a web environment and are also **built to be offline, downloadable,** so that they can be **used in a variety of contexts**—especially **rural contexts** and in places with **low internet connectivity**. I work in **inclusive design and accessibility** trying to figure out **how to scale both the design and implementation** of accessibility. Many people do not have accessibility in their products, and they definitely don't do it from the start because it's hard. This idea of **trying to design multiple modes at once,** correlating how things sound, the words that are spoken, the timing of things... You can design all those, but if they overlap, or they fire at the wrong times, **it's going to obscure your pedagogy** at the end.*

Brett was particularly interested in providing multiple ways for users to engage with content. He aimed to ensure that accessible simulations could be seamlessly integrated into users' learning.

In addition to taking environmental context into account in the design of emerging technologies for learning, PIs discussed the role of teacher experiences as critical to equitable co-design experiences. In the Collaborative Learning and AI project Building a Teacher-AI Collaborative System, Ying discussed her team's commitment to developing equitable technologies for learning:

> *One of the primary goals we're trying to address is to **find the right balance** between involving teachers but not increasing the workload. If you think about a spectrum, on the one hand, the **teachers manually create** instructional materials. And on the other hand, AI generates everything for them. This Teacher-AI collaboration approach is really **finding a sweet spot** within the spectrum. What we learned from our engagement with teachers is that there's **no one sense or solution for the right balance**. We saw a **wide variety among teachers**.*

Similarly to Ross, Ying reiterates the importance of accounting for user variability—in this case, the context of teacher experience—to support user-centered customization:

> *So, it's going back to how to develop a system that is **not too complicated** but **can accommodate** all these different needs. We want it to **offer autonomy to seasoned educators** but also provide **stronger guidance and support for those who are newer** to the profession. For us, the whole purpose of this proposal is to **offer customization**. But on top of that, we need to **allow teachers to customize how much customization they need** in this system.*

However, the creation of co-designed spaces for teaching and learning sometimes resulted in challenges that required pivots in approach. Flexibility to change course to meet emergent project needs was built into NSF EXPs. Brett described how this flexibility afforded him the freedom to address the challenges of losing key partners:

> *We had our expertise in multimodality, inclusivity, and virtual design, and **we lost the person on the physical side**. Given the timeline between **the pandemic**, that's pretty rough. Our ability to work with partners was actually a big issue across the board. A lot of **research partnerships with academia, high schools, and districts started to fall through**. And they've been slow to get back. I think that hit us, and probably many other researchers, pretty hard—especially those interested in co-design. The **exploratory nature of the RETTL funding** was very **powerful** because we had a little bit **more room within the questions**. The fact that it was exploratory in nature meant that the research questions that we've set out to solve were **not so bounded**. That meant **we could make a few pivots** within what expertise we still had.*

Similarly, situational shifts forced Roxanne to make pivots in her original project design—which was to develop a ChatGPT-like tool to help teachers scaffold questions for students—when ChatGPT was publicly rolled out ahead of her project timeline:

> *Our Principal PI was aware of GPT before it became ChatGPT, but it wasn't commercially available. So, when ChatGPT came out, he knew it was coming but **nobody knew what it was going to mean**. The question became, **"How do I parse this design challenge?"***

The flexibility afforded by NSF programs such as RETTL enabled PIs to address sizable emergent challenges—such as the pandemic or launch of a competing technology—while keeping their commitments to co-design.

Enabling equity in co-design and practice

Sheryl (Accessibility and Learning), Zachary (Virtual and Augmented Reality), Ying (Collaborative Learning and AI), Lorna (Accessibility and Learning), and Chad and Bill (Data Analytics and Simulations)

> *Enabling equity in the co-design of emerging technologies for learning required a) taking users' intersecting identities and needs into account when making design decisions, b) engaging in co-design practices with practitioners, and c) drawing on PIs own lived experiences to inform their values and mission-driven work.*

PIs felt that exploratory approaches were essential for understanding users' intersecting identities and needs through the exploration of disability and other plural and mutually occurring identities, as Sheryl explains:

> *I really wanted to **make sure that people with disabilities had access** to microcomputers, as we called them back then. A lot of projects, particularly if they focus on disability, narrow it to specific disabilities. **But they don't consider intersectionality.** I'd love to make the point that once you choose a group, you need to think about intersectionality. You need to think about **the other characteristics they might have**. It could be another disability. Or language, or culture, or gender and racial minority status that could impact their success and getting access to technology.*

When co-designing with users, PIs took intersectionality into account and used exploratory approaches to actively seek input from underrepresented voices.

This included co-designing with partners to inclusively address the needs of diverse users. Zachary, in discussing the Virtual and Augmented Reality project Using Augmented Reality to Enhance Attention in STEM Learning, shared these inclusive practices:

> *I think a key part is the **differences in perspectives and backgrounds** that the co-designers themselves have brought to this space. Some of them are interested in artistic **visual design and digital design**. Others are in computer science and really interested in the algorithm itself. Others are interested in **working in neurodiversity** and so they bring this perspective of how they can best develop these kinds of tools **with an eye towards universal design** to create tools that are **inclusive and accessible.***

Zachary highlighted the diverse perspectives and expertise of the co-designers involved in the project. This diversity enriched the project, as each co-designer brought a unique experience and viewpoint, to develop tools that are inclusive and accessible to a broad range of users.

For many PIs, exploratory approaches also supported the creation of infrastructures for equitable co-design with practitioners that lowered barriers to participation and uplifted practitioner expertise and autonomy. Ying shared how her team engaged in equitable co-design with practitioners:

> *The goal of this project is to **bring back the teacher's expertise** because they are central to students' day-to-day interactions, and they bring so much knowledge. We want to support them to **go beyond simply being consumers** to **actively shaping the technology's** development and usage. We see this as an opportunity to **expand the traditional co-design and participatory design research.***

We appreciate the co-design method to develop AI materials, but one limitation is that you can only work with a small group of educational practitioners, and once the product is developed, they ***do not have the autonomy*** *to make modifications of those products. We hope that by* ***creating a collaborative system****, we're* ***extending the time where the teachers can stay involved****... This could be an opportunity to make the materials* ***even more tailored to the instruction.***

Another opportunity related to this point would be ***lowering the technical barriers for teachers to participate*** *in this development. If you think about traditional development, AI-based learning materials are* ***controlled by people with technical backgrounds****, and teachers don't normally have the opportunity to do it themselves. With Generative AI and with these* ***more accessible system****s that we're going to develop, we're really* ***bringing the teachers back*** *to this so that AI is* ***no longer dominated*** *by a small sector of professions.*

Expanding traditional design approaches to create a collaborative co-design system that included teachers as co-designers was a central element in Ying's research. Essential to this equity approach is centering teachers in the development of the tools that will eventually end up in their classrooms.

Finally, adopting exploratory approaches allowed PIs to draw on their own lived experiences to inform their research and community engagement. For example, Sheryl shared that her background as a working-class first-generation college student turned mathematics teacher helped her connect with research participants and co-designers from diverse backgrounds:

I feel like I could pull this off because of my ***diverse background and my comfort****. My dad was a used car salesman. So, I was always around these mechanics and welders and watched my brother be encouraged to do that kind of stuff and me just stand back.* ***Finding my place*** *and going on to college was a big step in my family. I was a very good student, and I knew that. But it was only people in school that thought I should, including my math instructor. He said,* ***"Well, you going to college?*** *You're so good at math. You ought to do this." So, I became a math teacher.*

Sheryl's affinity for research at the intersection of disability, technology, and education was enabled by her interpersonal skill set born from her lived experiences. Sheryl credited her salt-of-the-earth, blue-collar upbringing as laying a foundation for attending to the needs of marginalized communities with empathetic understanding.

In addition to the impact of PIs' lived experiences on their research, engaging in exploratory approaches allowed PIs to design their research to be values and mission driven, as Lorna shared:

> *One of the missions of the Motion Light Lab is that every deaf child in* ***the world has a right to accessible language****, which means signed language—whatever is indigenous to their community and their culture since there's many different sign languages across the world. So really, Motion Light Lab's goal is to* ***end language deprivation in which deaf children do not have access*** *to language from birth.*

Motion Light Lab's mission was both personalized and equity centered—addressing barriers to ASL access and the marginalization of ASL as a language.

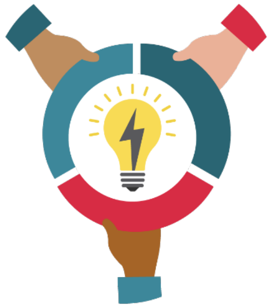
For other PIs we interviewed, their missions were aspirational and aimed to arrive at agentic and impactful outcomes for users of their technologies, as Chad described in his and Bill's Data Analytics and Simulations projects, Inquiry Space and Data in Space and Time:

> *We are* ***implicitly and explicitly founded on the principles*** *of encouraging exploration within STEM students' ownership and inquiry. Those have been* ***at the heart of everything*** *that we've done. Science, engineering, mathematics are the mediums that we work within but* ***not necessarily an end in themselves****. Really, the end all is* ***empowering students*** *to recognize that you can ask and answer questions that are unique and important to you, and that you can* ***use problem-solving skills*** *in lots of domains. And it turns out that science, math and engineering are* ***really good training ground****s for developing those skills that are* ***usable in all different aspects****.*

For Chad and Bill, shaping how people engage with ideas and data to address knowledge and skills gaps in scientific sense-making was central to their organization's mission.

Translating the mission and vision for their specific projects to address broader societal goals was also deeply related to PIs' hopes for the future impact of their work, as we detail below.

Emergent Impact Through Networked Communities



Broadening impact through innovation and expansion

Ying (Collaborative Learning and AI), Charles (Simulations), Sheryl (Accessibility and Learning), Nikolas (AI), Rebecca and Colleen (Augmented Reality), and Chad and Bill (Data Analytics and Simulations)

> *The initial investments that NSF made in PIs' research projects set the stage for future impacts that a) resulted in unexpected innovations and outcomes, b) moved beyond the original proposal, and c) scaled up emerging technologies for learning.*

PIs detailed the emerging impacts NSF's initial investment afforded their projects along three dimensions: securing new funding, conducting and disseminating new research, and expanding the reach of technological tools developed through NSF funding.

For example, Ying explained that the project insights from the Collaborative Learning and AI project Building a Teacher-AI Collaborative System led to securing new funding through the GBH grant Empowering Teachers to Collaborate with Generative AI for a new PBS media project. Charles shared that the Aladdin platform developed with the NSF funding from his Simulations project Science and Engineering Education for Infrastructure Transformation and Collaborative Research: Mixed Reality Labs have been incorporated into an international cooperation grant with Ukraine's Institute of Renewable Energy and the National Academy of Sciences to help rebuild Ukraine's energy infrastructure.

Regarding new research, Sheryl shared that the initial NSF-funded research from the Accessibility and Learning project Designing STEM Learning Environments for Individuals with Disabilities led to a longitudinal study of disabled children's experiences with technology into adulthood. Nikolas shared that research from the AI project Supporting Designers in Learning to Co-create with AI set the stage for the design of new interactive generative AI interfaces that will be developed into applications.

Finally, Rebecca and Colleen shared that their Augmented Reality project, Combining Smartphone Light Detection and Ranging with Augmented Reality, set the stage for expanding the reach of Physics Toolbox, an augmented reality physics sensor tool, from Rebecca's individual classroom to thousands of classrooms across the U.S. Chad and Bill also shared that CODAP, an open-source data analysis platform resulting from their Data Analytics and Simulations projects, Inquiry Space and Data in Space and Time, has become embedded in the infrastructure of education R&D with thousands of users, including researchers, developers, and students, per year.

At the start of these projects, the PIs did not know what the future impacts of their exploratory work would be. For many, moving beyond an original idea, to something larger and unexpected, was seen as a demonstration of impact, as Charles explained:

> *You say you want to do a proposal. Then, at the end of the project, you* ***create this overflow of impact that is beyond the original****, right? So that's a nice demonstration of broad impact. If you're only impacting the demographic community that you originally [set], then that's not broad.* ***That's anchored. Broad impact means that the problem, the user, is unexpected. The more unexpected, the better.*** *And that's the beauty of it, that's why it's an investment.*

For Charles, moving beyond the initial project parameters toward novel insights and applications was critical to using NSF funding as seed money toward achieving broader emerging impacts.

NSF's initial investment in PIs' projects also served to establish use cases for future stages and applications, as Bill explained:

> ***The early work was, as is so often true, about efficacy. Does this actually work?*** *Does it change what kids and teachers do in classrooms?* ***The second phase is scalability****: It works in these very contained situations,* ***but does it scale to large numbers of classrooms?*** *These* ***collaborations have led to proof of scalability****. We don't really know how many students use CODAP, because we don't ask students to log in. We just know that there are 500,000 unique IP addresses every year—several hundred kids on a given day****. So, we've gone from efficacy to scalability. The third step is longevity. How do you keep this alive? And that's what we're struggling with now.***

For many PIs, improving scalability, broadening reach, and strengthening sustainability were seen as significant indicators of future impact and challenges. Chad described the challenge of sustaining and expanding a project's impact:

> ***Our work is open source by desire to lower the barriers*** *in education. And we recognize that* ***raises issues for sustainability.*** *We're trying to* ***grapple*** *with that as we think about this o****pen-source ecosystem****. But I'm also sure that* ***the growth*** *that we're describing in terms of* ***impact on numbers and research*** *would not have been there if the model had been a paid business model.*

For Bill, both the positive outcomes and the challenges associated with their projects' impact ended up stretching them as researchers:

> *So, in a way,* ***CODAP has extended us.*** *We're having to* ***stretch to accommodate*** *it because it has been successful in* ***getting out into the world****. And now we have to* ***stretch to grow*** *that community and also to figure out* ***how to maintain it*** *in the face of changes in the underlying technology.*

Improving scalability, broadening reach, and strengthening sustainability incentivized PIs to connect with fellow researchers for community and support.

Mobilizing networked communities of practice

Marjorie (Simulations), Roxanne (AI), Erin (Collaborative Learning), Roxanne (AI), Lorna (Accessibility and Learning), and Ying (Collaborative Learning and AI)

> *PI participation in the CIRCLS networked community was essential to their engagement with NSF-funded interdisciplinary, exploratory research because it a) provided an environment that supports researchers' professional development through mentorship and camaraderie, b) used networked infrastructures to broaden interdisciplinary collaboration and address challenges and barriers to conducting interdisciplinary, exploratory research, and c) connected researchers with practitioners to prioritize implementation.*

Participation in the CIRCLS community promoted PIs' growth as scientists by tapping into a national expert group to challenge each other with new knowledge and perspectives, as Marjorie shared:

> *I think it's important that we **bridge the knowledge of technology,** and how it can be used and developed, with **subject matter experts**. I think that part of the NSF community through CIRCLS is as valuable as funded research projects because it really **helps individuals grow as scientists and researchers**. That's what I'm interested in. You're able to tap into a national group of experts to **challenge each other** and **help each other**, which is just really special. I really value the **community aspects** of all this.*

Participating in networked research communities provided a supportive environment for PIs to learn about different disciplines and engage in interdisciplinary work. As a result, CIRCLS was seen as one of the few networked communities that offered concrete avenues for broadened participation and interdisciplinary bridging, as Erin shared below:

> *I think CIRCLS in particular is essential in this kind of space where people are doing such innovative things **across disciplines**. It feels like an **important catalyzer** for this kind of research. There's been these dual goals of **broadening participation** and **bringing people** in who haven't traditionally been part of CIRCLS. Honestly, I feel **broadening participation** is really important. I think that bringing the current PIs into that conversation and **creating that bridge** is also important.*

As such, PIs felt that networked communities like CIRCLS provided mentorship, camaraderie, and support in fostering environments conducive to interdisciplinary engagement. For example, Roxanne shared her experience at a CIRCLS convening, where she discovered diverse design communities across various disciplines:

> *__I learned a lot__ when I went to the CIRCLS convening. I enjoyed seeing researchers across these __different disciplines__. It made me realize that, as much as engineering has a design community, computing also has a design community, and there's a whole different set of conferences and publication venues that they favor. It definitely opened my eyes to a __broader range of audiences__ and communities and places to propose work, to publish work, and to __learn from what other people are doing.__*

This exposure expanded Roxanne's understanding of various knowledge communities and introduced her to the conferences, proposal opportunities, publication venues, and audiences relevant to disciplines adjacent to her field of research.

Other PIs were appreciative of CIRCLS' supportive infrastructure for enabling collaborations with researchers in adjacent fields. For example, Lorna shared that her involvement with the 2023 CIRCLS convening made her feel part of a broader research community across diverse domains of interest to her work:

> *The __in-person convenings__ have been really a great way to learn about similar work in __parallel domains__ and see what other ways people are looking at these __intersections between technology and learning__. And it's been a great way to __share my work with the community__. So, I've had __collaborative calls__ with people. I've __explored grant proposals__ with people. This new proposal that we received good news about recently is a __collaboration with some colleagues from the CIRCLS__ community.*

The resulting interdisciplinary collaborations that emerged from PIs' participation in CIRCLS activities were viewed as positive examples of emerging and future impacts achieved through networked engagement.

However, PIs also described challenges—such as barriers to disseminating interdisciplinary exploratory research findings considered novel and unprecedented—as endemic to engaging in research that doesn't neatly fit into established academic disciplines, as Erin explains:

> *I feel that is one of the issues with exploratory research: What I'm doing in this project, and in my lab, __there aren't models__ for. __We're not following a template__ for how you build these technologies. And so, you __struggle__ at times because you have to __invent this all__. It means when you go to publish, then other people are looking at it like, __"I don't have a model for how to perceive this."__ That's something I've experienced quite a bit. So this is how I'm thinking about the __impact of this work,__ and the __opportunities that arose from it,__ and the ways in which I feel we're still working to __disseminate the outcomes__ to __influence the academic community__ more.*

In Erin's view, established research ecosystems do not currently support and amplify interdisciplinary exploratory work. This belief was echoed by several PIs who believed that current publication structures for disseminating interdisciplinary, exploratory research are still primarily siloed along established research trajectories.

Finally, many PIs we interviewed appreciated that the CIRCLS community brought researchers back to implementation by connecting them with practitioners, centering practitioner knowledge, and enabling future collaborations between researchers and practitioners.

Ying described her positive experiences engaging with practitioners through her participation in a CIRCLS Expertise Exchange session:

> *I participated in an **Expertise Exchange** session, which is a panel where I co-hosted with two other experts in the field. Our panel was around conversational AI. I liked **sharing our experiences** and also hearing what other panelists did. But more importantly, we had a lot of **discussions with the audience** who came to our panel. I got **a lot of questions** that were actually very **inspirational for my own research.** I also really like that the panelists are not just researchers but also **community members** who are **educational practitioners.***
>
> *We're not just researchers talking about how we develop conversational AI, we also have the **perspective from educators** to share what they think conversational AI might support, or might not be so helpful, in their classroom instruction. Just try to **bring us back** to the **actual implementation** piece, to how we could **make our research more useful** for the teachers and students. I've actually **been in touch with the educator** that was part of our panel. She has **connections with schools,** and I love to **get her insight** on how they see the **practical implications** of our research.*

Ying enjoyed working with practitioners across disciplines and appreciated the opportunity to facilitate discussions among CIRCLS community members. For her, this work included supporting participants in developing the skills needed to better understand and translate technical language from one field to another.

Discussion: Key Ideas

This thematic synthesis explored the nature, value, and impact of engaging in innovative interdisciplinary exploratory research projects through NSF EXPs. Although each project had unique characteristics driven by the diverse nature of the learning environments, participants, and emerging technologies being studied, taken as a whole, several key ideas became evident:

Exploration and Discovery Across New Frontiers

- Engaging in interdisciplinary, exploratory research creates a space for passion projects in underappreciated and understudied spaces.
- Exploratory research programs, such as NSF EXPs, create opportunities for collaborations across disciplines to support multidisciplinary and interdisciplinary work.
- Engaging with data in semistructured and unstructured problem spaces gives PIs the flexibility to focus on unanswered, novel, and reframed research questions to develop something new.
- Engaging in interdisciplinary, exploratory research provides the freedom to re-imagine the future for aspirational technologies in under-researched areas.

Equitable Co-Designed Learning and Practice

- Co-designing for teaching and learning requires the flexibility to change course to meet emergent needs of researchers, partners and participants.
- Developing equitable emerging technologies for learning requires engaging with learner variability and user-directed customization.
- When co-designing with users, it is crucial to take intersectionality into account and use exploratory approaches to seek input from underrepresented voices.
- Equitable, co-designed, interdisciplinary, exploratory research draws on practitioner expertise to support student interactions and knowledge building.

Emerging Impact Through Networked Communities

- PIs often do not know what the future impacts of their exploratory work will be—scaling beyond originally proposed ideas can be seen as a demonstration of impact.
- Participation in networked communities such as CIRCLS promotes PIs' growth by tapping into a national expert group with diverse, interdisciplinary knowledge and perspectives.
- Researchers who do exploratory projects that don't fit established research trajectories face barriers to disseminating novel or unprecedented research findings.
- Networked community feedback on the utility of emerging technologies across learning environments elevates the impact and reach of this interdisciplinary, exploratory research.

In preparing this synthesis, we discovered that PIs' experiences conducting interdisciplinary, exploratory research led to multiple opportunities, challenges, and lessons learned. Insights from NSF-funded exploratory research projects illuminated the flexible and adaptive nature of interdisciplinary, exploratory research and created space for PIs to develop contextually rich and novel understandings of understudied topics in Artificial Intelligence, Virtual and Augmented Reality, Collaborative Learning, Accessibility and Learning, and Simulations.

View Appendix B: Principal Investigator Interviews

Practitioner Reflections

Educators have been involved in CIRCL/CIRCLS since 2014. With many research projects focused on emerging technologies for learning, classroom and school-based practitioners in K-12 education are essential members of the community.

Practitioners have participated as co-designers, collaborators, and translators of research into practice. They have co-developed blog posts, professional learning webinars, and instructional resources, and participated in community expertise exchanges and convenings.

We asked Kip Glazer and Sarah Hampton, two practitioners actively engaged in Educator CIRCLS for multiple years, to reflect on their participation in CIRCLS, including the impact their participation has had on them professionally. Below are their insights.

Kip Glazer, Principal, Mountain View High School (California)

Why is participating in interdisciplinary, exploratory research interesting/impactful to practitioners?

As an educator and practitioner, I have always felt so strongly that we need to learn what the latest and most up-to-date researchers are discovering to perform our duties of serving our students well. I remember attending a CIRCLS convening in 2015, feeling frustrated that there weren't enough classroom-ready projects for practitioners. Fast forward to 2024, I saw a remarkable evolution with so many incredible projects that I could see our staff and students benefiting from!

Such changes were possible because of the work of researchers who incorporated practitioner voices over the years to broaden impact. Because learning science focuses on advancing the science of learning, it is closely tied to educational systems. It is unimaginable that the end users, such as teachers and school leaders, are not a part of the exploratory phases of any learning science research. At the end of the day, what would be the point of working on advancing the field of research when the end users don't receive the benefits? I am so glad to continue sharing my experiences and expertise as we work to improve learning for everyone!

What do educators value from attending CIRCLS convenings?

When I first attended the convening, I was a bit intimidated and overwhelmed by the brilliance I witnessed. However, connecting with such brilliant researchers and practitioners allowed me to gain new insights into the latest research projects. I found a group of like-minded people who could help me improve my craft. Still, I definitely felt my intellectual muscles being stretched by seeing the funded projects and speaking with the researchers who worked on them.

One of the most beneficial parts of the convening was meeting fellow educators who were searching for colleagues with understanding and passion for bringing research to their *local* *contexts*. I connected with so many researchers and practitioners around the country who taught me how their contexts influenced their work and how they had to adjust their implementation practices. Participation in the convenings has allowed me to have access to theoretical and practical knowledge to improve my own practices, and I have loved having the opportunities to partner with many beyond the convening whether it was to do a presentation together with them or write blog posts with them.

Sarah Hampton, Technology and Curriculum Specialist, Greenbrier County Schools (West Virginia)

Why is participating in interdisciplinary, exploratory research interesting/impactful to practitioners?

I love learning about more effective ways to teach and learn. When I first started noticing all the education research—all the journals, all the articles, all the learning experts and their work—I was honestly a bit discouraged. Here's all this good work and it's often not making its way into K-12 classrooms in a timely or transformative way. I've frequently thought about this problem like a reusable grocery bag that's left in the car. The bag has the potential to help, but it can't serve its purpose if it doesn't make its way into the store. Education research has the potential to help K-12 education, but it can't serve its purpose if it doesn't make its way into schools. What can be done to bridge that gap? I participate in CIRCLS to help build the bridge by sharing my practical lens with researchers whenever I can and by bringing the research back to practice.

Teachers want what's best for all of our students, and that's difficult to do. Sometimes we don't have the time or the bandwidth to help even when we want to. Knowing there are people consulting with practicing educators who are working on the challenging things makes me hopeful, especially because some exploratory projects are focusing on what works best for typical students and some projects are focusing on what works best for marginalized students. It makes me optimistic that we will learn better ways to help all our students as a result of this work.

K-12 educators often feel a disconnect between what's happening in theory and what's happening on the ground. As a math and science educator, I highly value scientific research and evidence-based practices, but it's difficult to have confidence in research—even research from learning experts—when the end users weren't included. When K-12 educators are included in projects from the onset, we know that scientific **and** practical expertises are represented and that the outcomes are more likely to succeed within the logistics of a K-12 classroom.

Learning about interdisciplinary, exploratory research brought an excitement and freshness to my teaching. For example, I learned about a project that developed an app that makes a phone's sensor information visible. The next week I strapped an old cell phone to a remote control car, and my students tried to map a readout of the phone's accelerometer to the car's movements. We also dropped the phone from a ladder onto a couch so students could see acceleration due to gravity during free fall. As another example, I learned about a remote opportunity in which my students could sign up for time in an Australian lab manipulating the distance between a radioactive sample and a Geiger counter. They were able to discover the inverse square relationship in an authentic way that never would have been possible in our rural school because of the expense and danger. For a third example, I was able to help my students understand how to solve algebraic equations by building their intuition through gesturing because of a project I learned about and the app the PIs developed.

I've grown to respect and trust this community. It takes some of the guesswork out of identifying resources. It saves time when I'm looking for high-quality materials because I have a starting point I can count on.

What do educators value from attending CIRCLS convenings?

As an instructional coach, my favorite thing about CIRCLS convenings is learning about a wide range of resources and best practices that I couldn't possibly accumulate from my own experiences. I think about convenings like a shopping spree at a hardware store. For a few days, I continuously stock my toolbox with high-quality tools. I may not have an immediate use for them, but, because they're useful, there will come a time when I or another teacher needs them. When that time comes, I can quickly produce the right tool.

In addition, convenings provide an opportunity to think about upcoming complex challenges in education with experts who each bring their unique perspectives and experiences. Talking through issues before they become mainstream gives me insights and prepares me to navigate them more effectively when they do confront our district.

I also appreciate meeting people at convenings who work on different aspects of education and learning about their projects. Plus, the 2023 convening intentionally included more educators, so I had the chance to meet other like-minded teachers and coaches. Building a network—knowing whose work to read, whose school has experienced similar challenges, or who to email when an issue arises—has been invaluable!

Recommendations

The 2022-2026 NSF Strategic Plan states:

> *Advances in how we learn, work, collaborate and explore are creating opportunities to greatly increase the rate of discovery and broaden participation in S&E. An increasingly diverse global research community is enriching the breadth of questions that can be asked and answered.*

The increasing rate of discovery and breadth of questions that can be asked and answered is particularly true in education—especially as technology brings profound opportunities to transform *how people learn* and *broader opportunities to participate in STEM.* In our four recommendations below, we highlight the supports needed by fields nurtured by the EXPs (and facilitated by the CIRCLS resource center), as they rapidly explore a breadth of highly innovative learning approaches made possible by rapidly advancing technologies.

Recommendation 1: Create consistent opportunities for the field to engage in future-oriented, interdisciplinary, exploratory research across programs and directorates.

NSF EXPs are time-limited programs that support collaborative, interdisciplinary, research. These programs emphasize bringing together investigators who otherwise might pursue funding in disparate, non-overlapping NSF directorates and programs. Exploratory research has grown and thrived with awards from these programs—indicating the field's strong interest in pursuing interdisciplinary design research with novel technologies for learning. The possibilities of AI and emerging technologies for education are capturing national attention from every educational role and perspective. A discovery-oriented, interdisciplinary, exploratory field is needed now more than ever. Thus, now is the time to consider how to create ***consistent and stable*** opportunities to bring innovators together across traditional NSF directorates and programs to collaborate, increase the rate of discovery, and address the challenges of broadening participation—and ultimately, to ask and answer questions about the future of teaching and learning that can only be asked and answered through such collaborations.

Recommendation 2: Intentionally nurture interdisciplinary research identities.

This and prior CIRCLS reports have consistently found strong evidence that researchers who participate in exploratory research come to identify it as a home for their life's work; we have found that researchers welcome an interdisciplinary, exploratory identity. Furthermore, Team Science continues to be a national strategy, recommended by the National Academies and resonant with prior NSF terms like "convergent science" or "interdisciplinary research." Additional steps by leaders in the field and at NSF could promote, celebrate, and amplify interdisciplinary team science projects and the identities of those who participate in them; at a more detailed level, investing in training and development opportunities to support professional growth for individuals engaged in interdisciplinary, exploratory research is essential to enabling broad and diverse participation in team science projects and programs.

Recommendation 3: Continue to uncover processes, methods, and flows that are uniquely important in interdisciplinary, exploratory research.

Peer-reviewed journal articles are an imperfect medium for communicating what is learned from exploratory, interdisciplinary research as peer review tends to favor established research trajectories. As indicated in this report, novel insights can be gleaned from contextually rich discussions with project PIs to learn how research teams come together, how the research is conceptualized and conducted, and to gain new perspectives on research design and process. For example, we uncovered that the interdisciplinary breadth of the field is more than just computer science and learning sciences, that the first year of a project is often particularly fertile for the transformation of ideas, and that exploratory research flows both from and to other types of funding and projects. Over the years, CIRCLS has worked closely with this research community to tell the story of their research processes in multiple ways—highlighting their core ideas, innovations, partnerships and, now, explorations in this current report. Recognizing the value of documenting and understanding how innovation happens, and amplifying processes for doing so, is essential for building strong research communities and could serve NSF in framing solicitations to highlight and support the unique character of interdisciplinary, exploratory research.

Recommendation 4: Support coordination networks to grow the field, synthesize outcomes, and amplify broader impacts.

Throughout this report PIs cite "networked engagement" as one of the strengths of this portfolio, and the value of having a resource center, such as CIRCLS, to facilitate that. Coordination networks establish long-term relationships with community members, provide a platform for collaborative work through meetings, reports, and dissemination opportunities, and enable deeper understanding of members' projects and work trajectories over time. Networks can identify approaches for brokering connections across interdisciplinary research spaces. Networks can also support the synthesis of program outcomes across multiple dimensions of interest for the program and larger research community. As the field for interdisciplinary, exploratory research on learning technologies continues to grow, support for networked collaboration will likely pay strong dividends.

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Appendices

Appendix A: Themes from Project Information Pages

Theme	Description/Key Takeaways	Project Examples
Expanding accessibility for learners through digital tools	Six projects were explicitly focused on developing digital tools that expand accessibility for learners with disabilities and neurodivergent learners. Some projects are at the stage of co-designing with learners to understand their needs. Other projects have built AI and mixed-reality tools such as sensory extension devices, ASL sign recognition, and screen readers to reduce barriers in STEM education.	• NeuroVivid: Developing and Testing a Maker Experience to Build Interest in Careers in Brain-Computer Interfaces Among Neurodivergent Youth: 2241380 • Enhancing Programming and Machine Learning Education for Students with Visual Impairments through the Use of Compilers, AI and Cloud Technologies: 2202632 • Using Augmented Reality to Enhance Attention in STEM Learning for Students with Executive Function Disabilities: 2202291 • Inclusively-Designing Sensory Extensions for STEM Inquiry Learning: 2119303 • New Dimensions of ASL Learning: Implementing and Testing Signing Avatars & Immersive Learning (SAIL 2): 2118742 • Broadening Participation in Informal STEM Learning for Autistic Learners and Others through Virtual Reality: 2005447 •

Alternative modalities in CS education	Seven projects used alternative modalities such as AI, AR/VR, tangible computing, and interdisciplinary learning to offer students opportunities to engage with CS. These projects often focused on the development of immersive, mixed-reality environments and AI tools that supported collaborative learning in CS. Notably, one project developed a framework that uses AI to generate code from natural language descriptions.	• An Embodied, Augmented Reality Coding Platform for Pair Programming: 2017042 • Collaborative Research: Learning Software Engineering by Contributing to Real Projects With Chatbot Assistance: 2303042 • Pair Programming with Intelligent Social Agents: 2302701 • Collaborative Research: Sizing Up Physical Computing to Explore Threshold Concepts in Cyber-Physical Systems: 2302787 • Open Player and Community Modeling as a Learning Tool: 1917982 • Strength Across Schools Partnership 2.0 to Teach Empowering Computational Thinking and Computer Science in Middle School English Language Arts Classrooms: 2317747 • Supporting Early Learning of Computational Thinking Using Mixed Reality Technology: 2118924
VR/AR tools in STEM education	Twelve projects developed VR/AR tools to better support understanding of STEM concepts ranging from computational thinking in early childhood classrooms to mining engineering courses in postsecondary settings. For science and engineering classes,	• Developing Hands-on Virtual Reality Science Laboratory Experiences: 1918045 • An Embodied, Augmented Reality Coding Platform for Pair Programming: 2017042 • Designing Mixed Reality Experiences to Support

	the tools provided simulations of laboratory conditions that allowed students to gain “hands-on” experience. In math, novel modeling and visualization of abstract math concepts in mixed reality created opportunities for multimodal learning. Two projects in younger grades also integrated a learner’s surroundings to ground learnings in computational thinking and math.	Participatory Complex Systems Learning: 2202431 • Combining Smartphone Light Detection and Ranging with Augmented Reality to Enhance Position-Based Teaching and Learning in STEM: 2114586 • Generalized Embodied Modeling to Support Science through Technology Enhanced Play (GEM-STEP): 1908632 and 1908791 • MathWalks: A Place-Based Mobile App: 2115393 • Collaborative Research: Worksite-Specific Safety Training Environments with Augmented Reality: 2302819 • New Dimensions of ASL Learning: Implementing and Testing Signing Avatars & Immersive Learning (SAIL 2): 2118742 • Impact of Utilizing Immersive Virtual Reality and Dynamic Assessment on Mining Engineering Education from the Community of Inquiry Perspective: 2202640 • Project mTEAM: Advancing Emergency Medicine Trainee Skills Using Multimodal Debriefing System in Simulation-Based Training: 2202451 • Bimodal Haptic-Mixed Reality Needle Insertion: 2118389

		• Supporting Designers in Learning to Co-create with AI for Complex Computational Design Tasks: 2118924
Innovations in workforce development	Four projects utilized AR/VR and AI technology for workforce training in high-stakes or high-risk situations that can't be easily replicated, such as medical emergencies and construction safety. Key achievements include new knowledge about AR's impact on workers' perception of safety hazards, the development of a multi-user VR experience, and increased training impact through narrative-driven games.	• Project mTEAM: Advancing Emergency Medicine Trainee Skills Using Multimodal Debriefing System in Simulation-Based Training: 2202451 • Bimodal Haptic-Mixed Reality Needle Insertion: 2118389 • Collaborative Research: Worksite-Specific Safety Training Environments with Augmented Reality: 2302819 • Innovating Online Ethics Training Using a Dynamic Narrative Learning Environment: 2202521
Broadening participation of marginalized groups through technology	Five projects are leveraging technology for the empowerment of underrepresented groups and expanding equity in the areas of literacy, social studies, data science, CS, and language learning. These projects are intentional about co-designing with underrepresented groups, particularly Black youths, Indigenous communities, and women of color. Notable key achievements include the development of novel learning algorithms for speech technology for young speakers of African American English (AAE) as well as a role-based, advocacy-driven	• From Data Literacy to Collective Data Stewardship: Technology Supported Community-Driven Solutions for Urban Youth: 2016982 • Collaborative Research: Improving Speech Technology for Better Learning Outcomes: The Case of AAE Child Speakers: 2202585 • Transformative Computational Models of Narrative to Support Teaching Indigenous Perspectives in K-12 Classrooms: 2119573

	data literacy platform for Black youths.	• Computer-Based Social Interactions to Facilitate Language Learning: 1757937 • Strength Across Schools Partnership 2.0 to Teach Empowering Computational Thinking and Computer Science in Middle School English Language Arts Classrooms: 2317747
Centering educators in AI/ML tools	Ten projects designed AI/ML tools that generate feedback for student work or teacher instruction to aid teachers in K-12 and postsecondary classrooms. These projects often utilize generative AI for tasks that are traditionally time and resource intensive (e.g., grading papers, monitoring student work, and providing personalized feedback in real time). Notably, one project focused on using AI to reduce bias in teaching through simulated environments while another integrated AI algorithms into web-conferencing tools to monitor team productivity. Four of the projects are in the process of co-designing with teachers to ensure that the final product reflects teachers' most pressing needs.	• Productive Online Teamwork Engagement through Intelligent Mediation: 2113991 • Collaborative Research: Development of Natural Language Processing Techniques to Improve Students' Revision of Evidence Use in Argument Writing: 2202347, 2202345 • An Intelligent Assistant to Support Teachers and Students in Simulation-Based Science Learning: 2302974 • Collaborative Research: Common Error Diagnostics and Support in Short-Answer Math Questions: 2118706 • Exploring Artificial Intelligence-Enhanced Electronic Design Process Logs: Empowering High School Engineering Teachers: 2119135 • Improving Student Learning While Decreasing Bias in Teaching Through Simulation: 2118849

		• Argument Graph Supported Multi-Level Approach for Argumentative Writing Assistance: 2302564 • CAREER: Grasping Understandings of Students Mathematical and Perceptual Strategies Using Real-Time Teacher Orchestration Tools: 2142984 • Using Neural Networks for Automated Classification of Elementary Mathematics Instructional Activities: 2000487 • Using AI to Focus Teacher-Student Troubleshooting in Classroom Robotics: 2118883
Co-designing with youths	Seven projects explicitly involved youths in the design process of the final product. In most cases, these youths are from marginalized groups with inequitable access to technology due to their race or disability status. Co-design varied in format—some projects sought the input of youths for more accessible tools and games while others focused on the development of new curricula. One project in particular conducted numerous summer co-design workshops and discovered the need to develop an open-source tool to engage participants in more active, equitable co-design.	• Broadening Participation in Informal STEM Learning for Autistic Learners and Others through Virtual Reality: 2005447 • Inclusively-Designing Sensory Extensions for STEM Inquiry Learning: 2119303 • NeuroVivid: Developing and Testing a Maker Experience to Build Interest in Careers in Brain-Computer Interfaces Among Neurodivergent Youth: 2241380 • Supporting Designers in Learning to Co-create with AI for Complex Computational Design Tasks: 2118924 • From Data Literacy to Collective Data Stewardship: Technology Supported

		Community-Driven Solutions for Urban Youth: 2016982 • Computer-Based Social Interactions to Facilitate Language Learning: 1757937 • Strength Across Schools Partnership 2.0 to Teach Empowering Computational Thinking and Computer Science in Middle School English Language Arts Classrooms: 2317747
LLM limitations and successes	Three projects mentioned the use of LLM in developing technology to support teachers. Two projects demonstrated successes with LLM in extracting key information from math and science work. For argumentative text, however, LLM struggled in identifying the relevant information.	• An Intelligent Assistant to Support Teachers and Students in Simulation-Based Science Learning: 2302974 • Collaborative Research: Common Error Diagnostics and Support in Short-Answer Math Questions: 2118706 • CAREER: Grasping Understandings of Students Mathematical and Perceptual Strategies Using Real-Time Teacher Orchestration Tools: 2142984

Appendix B: Principal Investigator Interviews

Participant name (Topic)	Project Abstract(s)	Project Resources
Chad Dorsey & Bill Finzer (Data Analytics & Simulations)	NDP: InquirySpace: Technologies in Support of Student Experimentation AND Data in Space and Time: Supporting Learners in Understanding and Analyzing Spatiotemporal Data	**CIRCLS Project Page:** INDP: InquirySpace: Technologies in Support of Student Experimentation: 1147621 **Concord Consortium Project Website:** InquirySpace **CODAP Website:** https://codap.concord.org/ **Tool:** CODAP Data Science Software
Brett Fiedler (Accessibility & Simulations)	Inclusively-designing sensory extensions for STEM inquiry learning	**CIRCLs Project Page:** Inclusively-Designing Sensory Extensions for STEM Inquiry Learning: 2119303 **Papers:** Investigating Sensory Extensions as Input for Interactive Simulations Sensory Extensions for Ratio and Proportion (PhET Interactive Simulations) Welcome to Paper Playground: Your Interactive Design Space
Lorna Quant (Accessibility & Learning)	New Dimensions of ASL Learning: Implementing and Testing Signing Avatars & Immersive Learning (SAIL 2)	**CIRCLS Project Page:** New Dimensions of ASL Learning: Implementing and Testing Signing Avatars & Immersive Learning (SAIL 2): 2118742 **Paper:** ASL Champ!: A Virtual Reality Game with Deep-Learning Driven Sign Recognition **STEM for all Multiplex:** Signing Avatars and Immersive Learning
Erin Walker	EXP: Improving Student Help-Giving with	**CIRCLS Project Page:**

(Collaborative Learning)	Ubiquitous Collaboration Support Technology: 1912044	EXP: Improving Student Help-Giving with Ubiquitous Collaboration Support Technology: 1912044 **Lab Website:** FACETLAB
Nikolas Martelaro (Artificial Intelligence)	Supporting Designers in Learning to Co-create with AI for Complex Computational Design Tasks	**CIRCLS Project Page:** Supporting Designers in Learning to Co-create with AI for Complex Computational Design Tasks: 2118924 **Paper:** Exploring Challenges and Opportunities to Support Designers in Learning to Co-create with AI-Based Manufacturing Design Tools Team Learning as a Lens for Designing Human-AI Co-Creative Systems **Video:** Exploring Challenges and Opportunities to Support Designers in Learning to Co-Create with AI-Based Manufacturing Design Tools
Zachary Alstad (Virtual & Augmented Reality)	Using Augmented Reality to Enhance Attention in STEM Learning for Students with Executive Function Disabilities	**CIRCLS Project Page:** Using Augmented Reality to Enhance Attention in STEM Learning for Students with Executive Function Disabilities: 2202291 **TERC Project website:** https://www.terc.edu/projects/augmentedef/ **Blog**: https://blog.terc.edu/emerging-leaders-at-terc-zachary-alstad
Colleen Megowan-Romanowicz & Rebecca Vieyra	Combining Smartphone Light Detection and Ranging with Augmented Reality to Enhance Position-Based Teaching and Learning in STEM	**CIRCLS Project Page:** Combining Smartphone Light Detection and Ranging with Augmented Reality to Enhance Position-Based Teaching and Learning in STEM: 2114586 **Papers:**

(Virtual & Augmented Reality)		Harnessing the Digital Science Education Revolution: Smartphone Sensors as Teaching Tools Evaluating learning of motion graphs with a LiDAR-based smartphone application **Tool:** Physics Toolbox Sensor Suite
Ying Xu (Collaborative Learning & Artificial Intelligence)	Building A Teacher-AI Collaborative System for Personalized Instruction and Assessment of Comprehension Skills	**CIRCLS 2023 Expertise Exchange Session:** Learning through Conversational AI: Technical, Learning Sciences, and Ethical Considerations **Papers:** "Rosita Reads With My Family": Developing A Bilingual Conversational Agent to Support Parent-Child Shared Reading Talking with Machines: Can Conversational Technologies Serve as Children's Social Partners? Same Benefits, Different Communication Patterns: Comparing Children's Reading with a Conversational Agent vs. a Human Partner What Are You Talking to?: Understanding Children's Perceptions of Conversational Agents
Charles Xie (Simulations)	Science and Engineering Education for Infrastructure Transformation AND Collaborative Research: Mixed-Reality Labs: Integrating Sensors and Simulations to Improve Learning	**CIRCLS Project Pages:** Science and Engineering Education for Infrastructure Transformation: 1721054 Collaborative Research: Mixed-Reality Labs: Integrating Sensors and Simulations to Improve Learning: 1124281 **Concord Consortium Project Page:** Education for Infrastructure Transformation **News:**

		NSF Announces International Multilateral Partnerships for Resilient Education and Science System in Ukraine
Ross Higashi Artificial Intelligence & Robotics)	Using AI to Focus Teacher-Student Troubleshooting in Classroom Robotics	CIRCLS Project Page: Using AI to Focus Teacher-Student Troubleshooting in Classroom Robotics: 2118883 Stem Learning and Research Center (STELAR) Project Page: Using AI to Focus Teacher-Student Troubleshooting in Classroom Robotics
Roxanne Moore (Artificial Intelligence)	Exploring Artificial Intelligence-Enhanced Electronic Design Process Logs: Empowering High School Engineering Teachers	CIRCLS Project Page: Exploring Artificial Intelligence-Enhanced Electronic Design Process Logs: Empowering High School Engineering Teachers: 2119135 Tool: Engineering Design Process Log (EDPL) Conferences & Proceedings: Belghith, Y., Moore, R., Alemdar, M., Rosen, J., Riedl, M., & Roberts, J. (2023, January). Examining Hard and Soft Skill Prioritization in High School Engineering Education. In *Annual conference of the American Educational Research Association.* Belghith, Y., Kim, J., Alemdar, M., Moore, R., Rosen, J., Riedl, M., & Roberts, J. (2023). Problem-solving or Solved Problems: Constricting Design Challenges in High-School Engineering Education to Avoid (Disruptive) Failures. In *Proceedings of the 17th International Conference of the Learning Sciences-ICLS 2023, pp. 2113-2114.* International Society of the Learning Sciences.
Sheryl Burgstahler	Synthesis and design workshop: Designing STEM learning	CIRCLS Project Page:

(Accessibility & Learning)	environments for individuals with disabilities	Synthesis and Design Workshop: Designing STEM Learning Environments for Individuals with Disabilities: 1824540 Longitudinal Study: 2016 Report of the AccessSTEM/AccessComputing/DO-IT Longitudinal Transition Study (ALTS) Report: Accessible Cyberlearning: A Community Report of the Current State and Recommendations for the Future AccessCyberlearning Proceedings: AccessCyberlearning 2.0 Capacity Building Institute (2019) Synthesis and Design Workshop: Designing STEM Learning Environments for Individuals with Disabilities
Marjorie Zielke (Simulations)	Exploring Social Learning in Collaborative Augmented Reality with Virtual Agents as Learning Companions	CIRCLS Project Page: Exploring Social Learning in Collaborative Augmented Reality with Virtual Agents as Learning Companions: 1917994 Paper: Exploring Social Learning in Collaborative Augmented Reality With Pedagogical Agents as Learning Companions
Wei Wang (Artificial Intelligence)	Enhancing Programming and Machine Learning Education for Students with Visual Impairments through the Use of Compilers, AI and Cloud Technologies	CIRCLS Project Page: Enhancing Programming and Machine Learning Education for Students with Visual Impairments through the Use of Compilers, AI and Cloud Technologies: 2202632 Paper: Python Programming Education with Semantics-Oriented Screen Reading for K-12 Students with Vision Impairments

Alina Reznitskaya (Collaborative Learning)	Collaborative Research: Conference: Promoting Cross-Disciplinary Dialogue Between Experts in Argumentation and Innovative Technologies	**CIRCLS Project Page:** Collaborative Research: Conference: Promoting Cross-Disciplinary Dialogue Between Experts in Argumentation and Innovative Technologies: 2230224 **Paper:** Professional Development in Classroom Discussion to Improve Argumentation: Teacher and Student Outcomes