Weaving the Fabric of Adaptive STEM Learning Environments Across Domains and Settings
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Weaving the Fabric of Adaptive STEM Learning Environments Across Domains and Settings

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How can we articulate a transformative vision of future STEM learning for diverse learners across domains and settings?

Abstract
This report reflects on an open-invitation design workshop designed to construct needed new collaborations with the learning sciences, assessment, and computer science communities to design integrative STEM learning environments.

Keywords
STEM learning environments; deeper learning; multimodal learning; learning sciences; educational data mining; interest-driven learning; learning analytics

Introduction

The goal of this workshop was to articulate a transformative vision of future STEM learning for diverse learners across domains and settings. We sought to forge a nexus among the (a) learning sciences, (b) assessment, and (c) data-intensive research (aka educational data mining) communities to formulate frameworks and tools for designing STEM learning environments.

Taking an approach for broadening participation through innovative designs that also centers educational equity, this project convened interdisciplinary teams to identify and propose forward-looking digitally-augmented STEM learning environments that bridge formal and informal learning contexts and which are inclusively responsive to the needs of every learner. This workshop effort was funded by the National Science Foundation in response to a call for “Principles for the Design of Digital Science, Technology, Engineering, and Mathematics (STEM) Learning Environments” for next-generation learning architectures (NSF 18-017). This Rapid Community Report articulates a future research agenda for the NSF as well as learning sciences researchers that could lead to new breakthroughs at the Human-Technology Frontier.

The open-invitation design workshop was convened at Stanford University. Dissemination through a public website and community outreach activities at relevant academic conferences was designed to ensure broad awareness of and access to these models, tools, frameworks, design principles, and research priorities for educators, researchers, and technologists.

The workshop was designed to construct needed new collaborations with the learning sciences, assessment, and computer science communities to design integrative STEM learning environments with robust in-process measures of adaptive learning that address key aspects of deeper learning, with a strong focus on learning that is NOT limited to a single setting or STEM subject— expanding across time, across settings, and to related STEM subjects (NRC, 2014).
To this end, workshop organizers identified three guiding themes for participants to consider as they shared the state-of-the-art in learning research, and deliberated on design principles for future learning environments:

1. How can digitally-augmented learning environments for integrated STEM learning scale successful efforts across diverse student populations and bridge formal and informal learning contexts?

2. What innovative research methods, statistical techniques, and modeling formalisms are necessary to embed theoretical models in data-driven computational approaches in order to capture, characterize, and support causal claims about individual and team-based learning, especially for complex, multi-source streaming data?

3. How can multi-domain threaded learning progressions be created for integrated learning and assessment of STEM subjects?

Workshop attendees

This workshop convened innovators advancing the state-of-the-art in equity-focused, technology-enhanced STEM learning, educational data mining and learning analytics, and educational measurement, to develop innovative ways to design and scale for a future of integrated STEM learning in an era of big data.

Participants were tasked to consider an infrastructure of generative new algorithms and knowledge models, psychometric models, and learner pathway models that could emerge from project activities at the intersection of such interdisciplinary perspectives to transform learning and assessment designs by incorporating signals from emerging designs from multimodal learning analytics and software for multi-faceted, multi-contextual measurement of social-emotional learning indicators and academic competencies.

The workshop participants generated a series of principles that they feel best frame the future of technology-enhanced STEM education consonant with the workshop vision of forward-looking, integrative STEM digitally-augmented learning environments that bridge formal and informal learning contexts and which are responsive to the needs of every learner.
Workshop structure

The workshop occurred on March 14-15, 2019. Workshop participants provided examples that represented the state-of-the-art in STEM learning environments. These included examples of learning that bridge K-12 formal/informal learning and/or which integrates STEM disciplines, as well as examples of rich data capture from industry. Prior to and during the workshop, participants created a shared repository of key papers on workshop-relevant topics, gave talks drawn from their work that connected to workshop goals, and shared elements of a vision of expansive learning. These were considered in cross-specialization group discussions, report outs, and collaborative writing processes, resulting in design principles and associated vignettes of envisioned learning environments.

Participants concurred on their frustrations over the lack of longitudinal STEM learning data on interests, achievements, socio-emotional learning (SEL) across domains and settings to support the desired vision of adaptive integrated STEM learning. Also, they felt a need centered on the importance of advancing the state-of-the-art of knowledge mapping, which serves to articulate relationships between learning progressions across multiple domains and contexts (Black et al., 2011). Researchers in attendance could not identify any integrated STEM learning examples yet of such multi-dimensional alignments of curricula and assessments.

Participants also found that there is a general lack of uses in STEM learning research of good/varied measurement methods for capturing multiple forms of data from which SEL constructs (self-management and emotion regulation; self-efficacy, social-awareness and empathy; identity; mindsets) related to STEM learning achievements can be derived. For example, the belief that effort will lead to increased competence defines a growth mindset, found to foster greater achievement and well-being across academic, emotional, and social domains. Although there are robust SEL Measurement Instruments, what is missing is their usage by researchers in relation to STEM learning, much less integrative STEM learning.
Weaving together data-driven integrated learning and assessment experiences across multiple STEM domains into threaded learning progressions of STEM subjects will be vital for learners’ developing adaptive expertise across STEM domains, rather than only within-domain learning progress.

**Key issues**

The workshop participants proposed a series of design principles that can shape the future of STEM learning environments aligned with the workshop vision of integrative STEM digital learning environments.

Through participant discussions and collaboratively-authored vignettes of learning environments, a set of design principles were distilled that captured the essential elements of future STEM learning environments. These principles reflect the need to merge best practices in teaching and learning with innovative technology (Clark & Mayer, 2016). These principles included:

1. Figure-Ground Flip Principle,
2. Measurement Principle,
3. Social and Generative Learning Principle,
4. Distributed Expertise Principle,
5. Learning Empowerment Principle, and

Together each of these six principles reflected the workshop participants’ vision of how learning technology can improve with a careful reconsideration of ways to integrate technology into learning spaces with a reinvigorated vision of the dynamic nature of learning across disciplines and contexts. These design principles are described in detail below.

**Figure-ground flip principle**

Traditionally, classroom experience is the figure (focus) and everyday life the [back] ground. This principle flips the relationship, making life outside of school ‘figure’, and in-school experience ‘ground’. One of the first considerations to be made in the integration of STEM education technology involves socializing the knowledge transfer problem (Pea, 1987). This involves brokering the relationships between real-world experiences and STEM classroom uses of technology (Barron & Darling-Hammond, 2010). As Nasir and colleagues note, “Often, people can competently perform complex cognitive tasks outside of school, but may not display these skills on school-type tasks” (Nasir, et al., 2014, p. 491)
Effective STEM education technology must carefully use real-world locales to ground sites for learning.

As technology brings real world STEM inquiry into schools in relation to real-world application and utility, students will be provided opportunities to incorporate telepresence, virtual labs, augmented reality, and virtual reality and agent-based modeling as a means to better understand their lived experiences and real-world phenomenon.

While learning with simulations and models of phenomenon is useful, learning which situates new technologies in real-world inquiry experiences must emerge as a priority.

Measurement principle
As new technologies emerge, these technologies must incorporate the capacity not only to make assessments-of-learning, but to broadly and effectively serve to support assessments-for-learning.

As back-end learning data and associated analytics continue to provide useful learning information, these assessments must be integrated into the STEM technology of the future to allow for real-time assessment and iterative refinements of digitally-enhanced instruction (Gane, Zaidi, Pellegrino, 2018).

Additionally, the measurements principle must be extended to the use of long-term performance assessment with technology. Embedding performance assessments in STEM learning technology will enable STEM technology to track and support students’ STEM interests and development of their competencies such as inquiry and argumentation-based thinking over time.

As scholarship and technology improve in parallel, they must engage in multidimensional measurement incorporating individual and group assessment practices (Worsley et al., 2016).

Social and generative learning design principle
One of the fundamental limitations of contemporary STEM technology is a limited incorporation of our scientific understanding of learning processes. Learning should be understood as active, socially constructed, and situated (Nasir et al., 2020).

Emergent STEM technology must be designed with the intention of fostering generative student learning.
Given our knowledge of learning, emergent STEM technology must be intentionally designed to produce the types of learner engagement that requires them to explain, argue, and share their STEM knowledge between learners, with teachers, and within their broader social communities.

STEM learning technologies should also have a social design focus, which expands learning opportunities for traditionally underrepresented students in STEM disciplines (Barron et al., 2014).

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**Distributed expertise principle**

As learners engage with STEM technology, the learners and participants in their communities must be included as learning agents, as ‘actors’ in an actor-network theory of learning (Barab et al., 2001).

- As knowledge is distributed among a dynamic set of contributors, STEM technology must carefully integrate expertise from all students and communities (Brown et al., 1993).

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**Learner empowerment principle**

Learning is far more than a simple cognitive task. Psychologists and sociocultural theorists have called for more expansive visions of how learning works (Nasir et al., 2020). A future of STEM learning technology must apply a more dynamic and culturally inclusive conception of learning and allow technology to foster STEM learning agency and self-efficacy for equitable participation.

- As technology is developed, special attention must be paid to ensuring that the technology supports full inclusivity of diversity with respect to gender, race, ethnicity, culture, (dis)abilities, and context.

- The STEM technology of the future must be one rich in learning opportunities that allow students to rethink who participates in STEM and provides students a sense of belonging that is embedded in the design of the learning technology and its uses for building STEM competencies and identities.
Human-virtual agent (VA) interaction co-evolution principle

At the dawn of personal computing, Douglas Engelbart established a vision of human-machine systems co-evolving with the distinctive strengths of each form of intelligence being leveraged.

- In recent years, virtual pedagogical agents have been providing many learning-support-relevant interactive features that can serve to backstop human teachers or otherwise support processes for engaging and deepening learning.

- The aim should be to create intelligent STEM learning systems that can interact with learners in natural, human-like ways to achieve better learning outcomes.

Recommendations for future work

The vision of adaptive integrative STEM technology-enhanced learning is one that must be approached by acknowledging the tensions and limitations inherent in taking such an ambitious approach to improve STEM learning with advanced technologies. The participants outlined five primary tensions that must be explored in an effort to reach the idealized goals outlined above and in the near-, medium-, and long-term education research agenda outlined in the full report.

- **Integrating Knowledge**: Learning progressions have been conceived primarily within specific domains only, yet the aim of NGSS-based science and NRC reports calls for adopting a more integrated approach to STEM teaching and learning. In recent years, there has been a thrust to integrate computational thinking, but there needs to be a more concerted effort to push toward disciplinary integration among other STEM domains as well. Given that the learning goals should sustain the aim of integrating science learning that weaves together disciplinary topics, technology must attempt to successfully walk the fine line between mapping learning progressions for linear growth and reflecting a more dynamic sense of interdisciplinary learning.

- **Capturing and storing multimedia data**: A foundational principle described above focuses on the careful and intentional use of back-end data to build better, more adaptively-responsive learning technology. An inherent challenge in these data uses involves the need to
store and have real-time access to longitudinal data across settings for creating comprehensive learner profiles to better serve learning needs. While many agree with the goals of data capture and use to support learning, the inherent concerns of data privacy and risks of creating ‘algorithms of oppression’ with discriminatory outcomes must be carefully considered.

...STEM technology developers and scholars must focus on the foundational role that teachers play.

♦ Questioning Inscrutability of AI Models: As technology adopts machine learning and artificial intelligence (AI) models, care must be given to how AI is used to make specific learning recommendations for learning. While teachers have the capacity to engage in differentiation and make real-time decisions about students’ learning needs, an emergent use of AI must carefully assess when and how AI databases make recommendations for what to learn, when to learn it, and why a learner should be learning a given topic.

♦ Involving STEM teachers in technology development: Years of research have implicated a lack of cooperation between teachers and educational technology developers as a factor that undermines the adoption and functionality of STEM technology. Increasingly, design-based implementation research is actively engaging teachers in design and data-driven redesign efforts to foster effective, equitable learning designs. As educational technology improves in the years to come, STEM technology developers and scholars must focus on the foundational role that teachers play.

♦ Developing Data interoperability in and out of school: A limitation of contemporary approaches to research is the false division between learning STEM in school and learning STEM in out of school contexts. As the STEM education technology of the future is conceived, developers and educators must pay more attention to ensuring the data that is derived from in school and out of school learning contexts are connected in meaningful ways. As back-end databases are employed, they must be done in a manner that allows for the integration of learning data collected during software use both in school and out of school environments (Niemi et al., 2018).

For further information about this workshop, the discussion at the workshop, a recommended research timeline, and the repository of previous research, please read the full white paper.
References


Resources

Workshop website:  
https://hstar.stanford.edu/workshops/nsf-design-synthesis-workshop/


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Appendix:

Workshop Participants:

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