Infrastructures to Support Equitable STEM Learning Across Settings

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STEM learning is a process that unfolds through dynamic interactions over time and across settings. Formal education in schools is not the only—or necessarily the most significant—context for STEM learning.

Important opportunities also occur in out-of-school time (OST), including during designed programs before and after school, through the support of mentors, and via online communities (Adams, Gupta, & Cotumaccio, 2014; Bell, Tzou, Bricker, & Baines, 2012; Ito et al., 2013). Collectively, these opportunities make up a "STEM learning ecosystem," which comprises the interactions among learners, the settings in which learning occurs, and the learners' communities and cultures (National Research Council, 2015, p. ES-2).

Advancing equity in STEM requires providing young people of all backgrounds with a rich array of resources for learning across the multiple settings of their lives—in school, in community organizations, in neighborhoods, in families, and in online communities. A recent National Research Council (2015) report called out the need to map learning opportunities in communities and explore how youth navigate those opportunities. The field could promote equity, the report suggested, both by addressing gaps in the STEM learning ecosystem and by connecting youth from underrepresented groups—girls, for exam-

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ple, and African-American, Latino/a, and Native youth—to existing opportunities. The report also called for building a lasting "STEM learning infrastructure" (p. ES-2) to address inequities that limit the access of youth from underresourced communities to STEM careers and academic pursuits (National Research Council, 2015).

This paper outlines principles for building a diverse and connected ecosystem and the features of a STEM learning infrastructure to promote equity. Our recommendations are derived from a review of literature on general strategies for leveraging diversity in STEM learning and on specific programmatic efforts to promote young people's learning across settings. The research on equity shares a premise that diverse everyday experiences are a resource for—rather than a barrier to—young people's learning (Gutiérrez & Rogoff, 2003; Nasir, Rosebery, Warren, & Lee, 2014). The goal of STEM education, then, should be not to eliminate perceived deficits in students, their families, or their communities, but to find connections between each of these and disciplinary knowledge and practices (Warren, Ogonowski, & Pothier, 2003).

Because the literature on programs that make explicit attempts to promote learning across settings is relatively new and sparse, we sought to identify programs that were grounded in this premise and that had some evidence of positive youth outcomes. Our review included designs that show at least some promise of expanding youth access to STEM learning in and across settings. The result is a set of principles for designing equitable STEM learning ecosystems and a corresponding set of infrastructures necessary to support such systems.

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Design Principles to Support Equitable Learning Across Settings

Our literature review revealed five design principles for translating ideas about equitable STEM learning ecosystems into program structures. To promote equitable cross-setting learning, afterschool programs must:

1. Draw on values and practices from multiple settings to articulate shared learning goals and to identify resources that can help to meet those goals
2. Structure partnerships so that multiple stakeholder groups can co-design initiatives to promote learning across settings
3. Engage young people in building stories, imaginative worlds, and artifacts that make connections and have meaning across learning settings
4. Help youth identify with the learning enterprise by supporting and naming them as contributors to authentic endeavors
5. Intentionally broker youth learning across settings, including preparing educators and family members to be brokers

These design principles have been applied to the development of learning opportunities, but they have not been widely tested as a set. Rather, they are useful guides that can be verified through empirical study and then refined or even dropped (Bell, Hoadley, & Linn, 2004). These five design principles are intended to serve as provisional guides to be tested and refined over time through research and development.

Draw on Values and Practices to Articulate Shared Learning Goals

The first design principle for equitable STEM learning is to draw on values and practices from multiple settings to articulate shared learning goals and to identify resources that can help to meet those goals.

Educational design research typically focuses on a single learning environment. Designing for inclusive learning across settings requires diverse perspectives on learning goals, challenges, and resources to be leveraged; for example, practices for supporting learning are organized differently in families than in schools (Rogoff et al., 2007). Afterschool programs need to understand young people's cultural norms in order to use those norms as learning resources. To do so, they must build relationships with communities and families (Brown & Nicholas, 2012).

An example of an effort to draw on local communities' values and practices to support STEM learning is the Ethno E-textile project (Kafai, Searle, Martinez, & Brayboy, 2014). The project used electronic textiles and local Native American crafting and sewing practices to help students learn about engineering and computing. The project involved close collaboration among researchers, a teacher, and members of the local cultural resources department to identify links among computing practices, craft practices, and local knowledge.

The researcher-facilitators explicitly drew out the computational principles already present in local crafting cultures. They challenged youth to reflect on how computation could be useful in their community and reflect their own interests and identities. Creating designs that reflected their hybrid experiences in both Western and indigenous communities, students easily connected the e-textile project and their Native Arts class. This project underscores how community value systems can provide a context for learning about computing while linking home and school spaces (Searle & Kafai, 2015).

Involve Stakeholders in Co-Design

The second design principle is to structure partnerships so that multiple stakeholder groups can co-design initiatives to promote learning across settings. Co-design in education is a highly facilitated process that engages people who have diverse expertise in designing, developing, and testing educational innovations (Penuel, Roschelle, & Shechtman, 2007). In structuring partnerships to support equity, leaders must consider not only which stakeholder groups need to be involved, but also the history of these groups' relationships. Inequities can be perpetuated when designers presume that everyone can and will participate equally despite a history of disenfranchisement of people from nondominant communities.

A collaborative effort led by Megan Bang and colleagues (Bang, Medin, Washinawatok, & Chapman, 2010) with the Menominee people in rural Wisconsin and with Native people living in Chicago illustrates this intentional approach to co-design that accounts for historical inequities. This partnership aimed to increase the science achievement of Native American students and their representation in science-related professions while deepening students' "community-based ways of knowing," which reflect indigenous scientific epistemologies (Bang & Medin, 2010, p. 1009).

Countering the long history of research conducted in indigenous communities without consideration for cultural values and without involving the communities in the research, Bang and colleagues designed a form of participatory action research (Hermes, 1999) that fully engaged the indigenous communities. The approach included input from local elders, support from tribal institutions, use of traditional language, respect for cultural values, and broad community participation in the research activities. The inclusion of stakeholder groups throughout the research and development process was vital to the design of learning across settings and the successful youth outcomes the researchers documented (Bang & Medin, 2010). Promoting equitable cross-setting learning should not be the job of just one person or organization. Partners working across settings need to make sure many voices are involved.

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Make Connections Across Settings

The third design principle for equitable STEM learning suggests that afterschool programs engage young people in building stories, imaginative worlds, and artifacts that make connections and have meaning across learning settings.

Our literature review uncovered several afterschool programs that have engaged participants in co-constructing narratives that have significance in multiple settings. *Transmedia storytelling* (Jenkins, 2010) is a design approach for creating a single story that audiences or learners can experience across different media. It typically involves building an imagined world in which plots unfold across various media as participants not only identify with characters but also add to the narrative itself. Participants can shape the story by adapting it in their own creative writing, as is common in fan fiction (Chandler-Olcott & Mahar, 2003).

Transmedia storytelling is increasingly common in the entertainment sector. In recent years, educational broadcasters have begun to use transmedia storytelling to design cross-setting innovations for children. An example is a set of interventions to promote low-income children's mathematics and science learning (Pasnik & Llorente, 2013; Penuel et al., 2010). The preschool-based interventions used public television programs targeting four- and five-year-olds, offering guided viewing of programs, game play, and hands-on activities to promote specific learning goals in mathematics and science. Because the programs appeared on broadcast television and the interventions included resources for parents, families could extend their children's learning at home. More parents in the intervention group reported that their children talked with them about ideas in the science curriculum than did parents of children who were not part of the intervention group (Penuel et al., 2010).

Name Youth as Contributors

The fourth design principle for cross-setting STEM learning is to help youth identify with the learning enterprise by supporting and naming them as contributors to authentic endeavors. Learning always involves becoming a certain kind of person, that is, developing an identity. Identity development involves appropriating, or "making one's own," the tools and practices of a discipline (Hand & Gresalfi, 2015; Nasir, 2010). Young people who identify as science learners are more likely to access science learning and to persist and succeed in it. However, historical patterns of STEM participation exclude women and members of particular racial groups, including Latinos, African Americans, and Native Americans. Intentionally developing positive science learning identities is critical for expanding equity in science education.

Designing for identity development requires giving young people opportunities to contribute to authentic endeavors and to have their contributions recognized. In authentic endeavors, young people have a say in the purposes of the learning activities in one setting, an experience that prepares them for action in another setting (Ito et al., 2013; Zeldin, 2004; Zeldin, Camino, & Mook, 2005). Authenticity is evident when young people participate in planning, take on different roles according to what is needed in the activity, and think strategically (Heath, 2001, 2005); authenticity also emerges when the boundaries between school and community are blurred (Gutiérrez & Vossoughi, 2010; Polman & Hope, 2014). Having a say in and contributing to the organization of an activity in one setting prepares youth for future activities in which they are expected to show initiative, define problems to be solved, and take action to solve them.

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A good example of designing for identity development is Green Energy Technologies in the City (GET City) at the Boys & Girls Club in a Midwestern city (Calabrese Barton & Tan, 2010). The program serves primarily middle-school-aged youth from nondominant communities. As in many other science programs in or outside schools, youth learn how to engage in key science practices, such as planning and conducting investigations, analyzing and interpreting data, and communicating scientific information. Unlike many other science programs, however, GET City gives youth a considerable say in the activities: Adult staff regularly enlist them to co-plan activities and then adjust course when youth propose changes. At the insistence of the youth themselves, their investigations brought them into the community, where they conducted street interviews about residents' experience of urban heat islands. The youth also presented the results of their investigations to city officials. As Calabrese Barton and Tan (2010) document, a number of GET City participants have appropriated identities as "community science experts" (p. 21), that is, as persons who are capable in science and can generate evidence related to culturally relevant environmental concerns in their communities.

Intentionally Broker Learning Across Settings

The fifth design principle is to intentionally broker youth learning across settings, preparing both educators and family members to be brokers. *Brokering* refers to helping people move from one setting into another that might otherwise be inaccessible (Ching, Santo, Hoadley, & Peppler, 2015). Brokering can be as simple as telling an acquaintance about a job opportunity, or it can involve extended, deep interaction to help someone master a complex new work practice. Youth from low-income, immigrant, and marginalized communities may have less access to the social networks commonly leveraged by middle-class families to broker students' learning across multiple opportunities—internships, summer camps, and advanced coursework, for example (Duncan & Murnane, 2011). Because people who act as brokers often occupy positions between different networks of people and practices, brokering is sometimes called "boundary spanning" (Tushman, 1977). Effective brokering expands not "know how" but "know *who*"—knowing which people or groups can provide personal or social support or have knowledge, skills, or resources to share (Wellman & Frank, 2001).

Having a broker can be important to getting a job in a STEM field. Brokers help young people navigate educational requirements, bureaucratic procedures, and implicit expectations regarding successful career pathways (Stevens, O'Connor, Garrison, Jocuns, & Amos, 2008). In addition to "know who," brokering requires "know where"—knowing networks of people and places where learners can pursue deeper learning, whether in formal educational settings, work, play, or civic institutions.

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Programs like the Lang Science Program at the American Museum of Natural History, which helps to broker access to STEM fields for underrepresented groups, are purposeful about building personal and institutional links among middle and high schools, community colleges, and four-year schools (Adams et al., 2014). Lang participants commit to seven years of work at the museum, where they have opportunities to engage in ongoing research in fields such as zoology, genetics, paleontology, and astrophysics. The program is an intentional effort to support youths' long-term engagement by developing initial interests in STEM, fostering STEM-linked identities, brokering access to high school and college opportunities, and ultimately supporting pursuit of STEM careers. The Lang program team engaged in a retrospective analysis (Adams et al., 2014) to understand how long-term participation in such OST programs shapes young women's interest, motivation, and ability to pursue and persist in STEM majors. Preliminary findings from a retrospective study of six alumnae show that the program played a significant role in the young women's STEM identities and career trajectories. The program brokered access to the museum itself, to science subjects that likely would otherwise have been inaccessible, and to science professionals who broadened the young women's awareness of the variety of science-related professions.

Combining Design Principles

Ideally, program designers integrate all five principles to design for equitable learning across settings. For example, a program might integrate principle 1 with principle 5 by encouraging facilitators to elicit youths' values and interests and then link them to activities in the community. The same program could recognize youths' accomplishments in those activities through a digital badge system that is shared across multiple partner institutions, integrating principle 2 and 4. The badge system could integrate principle 3 by using a story or "pathway" metaphor to encourage youth to pursue more and more challenging activities.

Supporting Infrastructures for Learning Across Settings

To implement the five cross-setting equity-oriented design principles outlined above, programs need to build supporting infrastructures that can connect organizations and communities (National Research Council, 2015). *Supporting infrastructures* are "behind-the-scenes" material resources and processes that are critical to the functioning of any learning ecosystem; they must be built and maintained over time.

Focusing on infrastructures is critical to diagnosing inequity and promoting equity (Hall & Jurow, 2015). By making visible the infrastructures that enable many economically advantaged youth to pursue coherent STEM learning opportunities, we can see what must be put into place to provide such opportunities to youth from underresourced communities. Most infrastructures are largely invisible; it takes deep investigation to expose the work infrastructures do, let alone to redesign them. Yet this redesign is a core task of systems change. The design principles outlined above require new infrastructures to support equitable learning across settings.

Adequate Material Resources

One reason advantaged youth can pursue varied STEM learning opportunities is that their families can afford to pay for extracurricular programs, while lower-income families cannot (Duncan & Murnane, 2011). Most of the initiatives described above were funded by grants and therefore were accessible to low-income participants because participation was free.

Resources are needed to support both programs and families. Very little grant funding supports scaling and sustaining programs. Unstable funding for informal organizations may limit their ability to plan, staff, and sustain innovations. Further, research suggests that one reason young people from lower-income families suspend pursuit of STEM interests is that they lose access to material resources, such as transportation or computers, that support their participation (Van Horne, Van Steenis, Penuel, & DiGiacomo, in press). Promoting equity means providing funding to sustain programs and to lower or eliminate the costs of participation for low-income youth. One solution is for cities and states to provide base funding for equity-focused STEM initiatives.

Support for Parents

Middle- and upper-income parents often play a wide variety of roles in supporting their children's learning, including brokering access to OST opportunities. Beyond brokering, parents can play many different roles in supporting their children's STEM-related learning, from collaborator to teacher to co-learner (Barron, Martin, Takeuchi, & Fithian, 2009). Lower-income parents may need support to learn to take on these roles. Designing opportunities for parents to participate with their children in STEM learning activities holds promise as a means of expanding parents' repertoires for supporting their children's learning (Roque, Lin, & Luizzi, in press). Additionally, intentional efforts to raise parent awareness of learning opportunities that can allow their children to persist in STEM activities may be a crucial part of a robust learning ecology.

Strong Ties Among Organizations

Strong social relationships and links among organizations in neighborhoods are important for educational attainment in schools (Johnson, 2012). They are also important resources for brokering access to opportunities in STEM. In order to broker young people's access to new STEM learning opportunities, adults need to know about the opportunities (Ching et al., 2015). Adult leaders' own community ties to other adults with relevant expertise are important sources of such information.

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Systems for Linking Youth to Opportunity

One of the greatest challenges to STEM equity is lack of access to OST opportunities that would allow youth to discover or deepen their STEM interests. One reason is that neighborhoods vary in the abundance and diversity of youth programs they offer (Kehoe, Russell, & Crowley, 2016).

The Chicago City of Learning is a citywide partnership in which more than 170 organizations engage young people in roughly 4,000 OST activities, many of which involve STEAM (STEM and arts) learning. The program's website enables youth and their families to identify activities based on their interests. The website is also used to recognizing youths' accomplishments in OST programs, recording digital badges such as Science Research, Robot Instructions, and Peer Mentor. Researchers have used the site's data to map the locations of STEAM programs and to identify neighborhoods where more opportunities are needed (Pinkard et al., 2016). This research builds on smaller-scale studies that underscore the transportation challenges low-income youth face in accessing OST learning opportunities (Chin & Phillips, 2004). The partnership is using the researchers' maps to explore where to expand opportunities for youth.

Partnerships and Coalitions

Long-term partnerships among organizations in a community and coalitions that advocate for access to educational opportunities can be an important part of a supporting infrastructure for equitable learning opportunities across settings. The Hive Learning Networks, active in several cities including New York and Pittsburgh, are an example of partnerships among youth organizations that focus on enhancing interest-related learning opportunities (Larson et al., 2014). At Hive meetings, organizations share strategies and engage in joint design work to build new pathways for youth. Community-wide partnerships can facilitate young people's access to learning opportunities across settings; when organizations collaborate, they can design pathways for developing deeper and deeper expertise in an area (Falk et al., 2016). Coalitions and advocacy organizations can also build a broad base of support for expanding opportunities for youth (Renée, Welner, & Oakes, 2009).

Designing Learning Opportunities and Building Supporting Infrastructures

The examples in this paper illustrate the possibilities for designing equitable STEM learning opportunities across settings. They elaborate on a vision presented in the 2015 National Research Council report, which calls for building resilient STEM learning ecosystems where youth can access many learning opportunities that are coherent and build on one another. The components of a supporting infrastructure constitute the conditions for building such ecosystems at the scale of a neighborhood or city. That such supports exist in some areas already provides hope that an ecosystem approach can expand opportunity for youth from under-resourced communities.

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Our framework articulates broad design principles. Developers of cross-setting initiatives will need to elaborate on these principles to address the specific needs in their communities. Taking into account home and community values and practices when identifying learning goals, structuring partnerships to co-design learning opportunities with nondominant communities, and engaging youth in storytelling to facilitate meaning-making all serve as ways to engage youth from underrepresented groups in STEM learning across settings. Similarly, programs must purposefully identify youth as contributors to the scientific enterprise and must intentionally broker youths' access to opportunities.

In addition, the supporting infrastructures described above must be considered when designing for cross-setting learning. Funders must address the lack of resources to scale and sustain programs in order to reduce barriers to youths' access to STEM learning. Lower-income families need support to better foster their children's learning. Adults need help to identify and connect youth with expertise in the community; similarly, youth need better access to information about OST learning opportunities. Partnerships that bring together community organizations to develop equity-focused educational initiatives can increase cross-setting STEM opportunities for youth.

Applying these design principles to promote equity and building supporting infrastructures to link youth to new opportunities will help to expand STEM learning opportunities for all youth.

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