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Advancing transformative STEM learning: Converging perspectives from education, social science, mathematics, and engineering

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Abstract. Society faces emerging challenges that require re-envisioning what it means to know and use science, technology, engineering, and mathematics (STEM) and who are STEM scientists. We advocate for a transdisciplinary framework for participatory STEM learning based on the culmination of the authors' designing and complemented by reviews of extant works in youth STEM learning and engagement. Data literacy, geospatial reasoning, and community science are cornerstones in our framework because of their power to leverage and integrate the four STEM disciplines. Youth with their families are authors and designers in community problem-solving using data literacy and geospatial reasoning through participatory community science to question, analyze, and design solutions empowered by their lived experiences. Through partnerships with community organizations, families, youth, and STEM practitioners, we discuss how to develop and use tools and methods to design and build better spaces for youths' communities. Our aim is for more authentic, inclusive, and empowering learning opportunities that broaden youths' STEM participation. We describe our framework and the underlying commitments, design principles, expected outcomes, and limitations.

Keywords: STEM education, data literacy, geospatial reasoning, participatory community science, transformative learning framework

1. Introduction

Society faces emerging challenges that require re-envisioning what it means to know and use science, technology, engineering, and mathematics (STEM) and who are STEM scientists. From the current pandemic to climate change, we face events that require the global community to lean into solving problems collectively and at scale. These problems affect communities differentially, and our call to re-

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envision STEM is an effort to address the inequities that persist across social systems. Systemic issues of injustice calling for transformational approaches to STEM learning must broaden the participation of diverse youth and their communities so that *they* may generate solutions for local problems that have global implications. Our team draws upon the transdisciplinary expertise of mathematics educators, social scientists, engineers, technologists, and community-based organizers to advance a framework for designing transformational STEM education that positions youth and their communities as STEM authors and actors. We argue that such a transdisciplinary approach is vital for broadening the diversity of participants in STEM learning. Our call for re-envisioning what it means to know and use STEM knowledge and practices is framed within the United States (U.S.) and we draw upon theoretical ideas that have been used across geopolitical contexts. We encourage readers to consider applying these ideas to an international context. Our aim is not just another call for the reform of STEM education driven by the need to fill a "gap" in diverse youth achievement. We argue that community-engaged STEM learning is essential for redefining what is STEM, who does STEM, and how STEM is accomplished.

This position paper presents a framework for designing youth- and family-driven place-based STEM education to promote data literacy and geospatial reasoning by using accessible and relevant tools and technologies for solving community-based problems. We focus on the intersection of data literacy and geospatial reasoning as fertile ground for participatory community science where youth and families are well-positioned to identify needs and problems, pose place-based questions, use a variety of tools, and create community-centered solutions that can be prototyped and iterated to address current and related future issues. One may ask, why are we focusing on this intersection? We believe that the intersection of data literacy and geospatial reasoning is critical to the everyday activities of youth and their families and these areas have a large impact on the quality of their lives.

Geospatial reasoning, the reasoning about space, place, and dimensionality, is place-based (National Research Council, 2006). It builds on the funds of knowledge (González et al., 2005; Moll et al., 2013) that youth and their families exercise as a part of formal and informal learning and shapes how people use and come to understand their place in a community. Likewise, vast bodies of data are being gathered via families' use of online web searches and geolocation services that continually shape their lived experience via algorithms and data sharing. Data literacy, the ability to read, write and communicate data, is an essential skill and one that has broad application (Bargagliotti et al., 2020). Youth and families are bombarded with data displays in this era of big and small data that demand sense-making and that have social and political consequences for their lives from who represents them in government to the likelihood of contracting a virus with long-lasting impact (Kitchin & Lauriault, 2015). The intersection of data literacy and geospatial reasoning is an untapped area of STEM learning with real impact and relevance for diverse groups and that is in high demand for STEM fields and careers.

Drawing from the teams' transdisciplinary practices and principles, this framework focuses on the needs and experiences of youth and families within communities. We position youth and families as essential to articulating the multi-dimensional nature of their needs and experiences to engage in human-centered participatory design (Bødker & Kyng, 2018; Marsden et al., 2008; Meyer & Norman, 2020) informed by sociocultural theories of learning (Gutiérrez & Rogoff, 2003). We elevate the varied knowledge bases of youth, families, and community organizations to curate and act upon evidence (Lippman, 2010), take up integrated ways of reasoning endemic to solving real-world, complex problems (Makar et al., 2011; Sadler & Zeidler, 2005), and posit that, in collaboration, youth, families, and community organizations are positioned to design solutions to community problems *and* amplify counter deficit-based narratives on diverse youths' STEM capacities. The paper's authors have foundational experiences across three continents and recognize that other educational systems' resources, policies, and practices will shape how this framework may be used in different educational contexts.

We propose a framework to pilot STEM initiatives for youth and families in the U.S. in anticipation of expanded initiatives aligned to local conditions around the globe. First, we explore current participation barriers for diverse youth to STEM education and the latest thinking about closing those gaps. Next, we present the rationale for our focus on STEM knowledge and practices. We discuss tactics for breaking STEM participation barriers through data literacy, geospatial reasoning, and participatory learning design as contexts for the convergence of STEM subject areas. This discussion is followed by a framework for STEM education presented as an approach for overcoming traditional challenges facing STEM education. We then discuss the possible outcomes, limitations, and further considerations of our framework.

2. Systems barriers to participation in STEM education and STEM careers

Approaches to U.S. STEM education have inadvertently created participation barriers for diverse youth and their families. These barriers result from overly narrow views of knowledge and practices that disrupt participation in STEM across kindergarten through grade 12 (K12) and collegiate education (Champion & Mesa, 2018; Kelly, 2009). Guidelines on the content of U.S. K12 STEM education have attempted to broaden beyond lists of topics to include discipline-based practices, e.g., Standards for Mathematical Practice (NGACBP & CCSO, 2010) and Science and Engineering Practices (NRC, 2013); however, these policies also amplify divisions between school science and math and the content of STEM used every day (Booker & Goldman, 2016; Carlone et al., 2016). These barriers between formal and informal STEM learning are echoed in many international educational settings (Morris et al., 2019; Yang et al., 2021). As a result, limited perceptions of STEM disciplines in school subjects have the potential to marginalize those who draw upon varied ways of reasoning and participating, suggesting those who engage in these epistemically diverse ways are not welcome (Philip et al., 2016). While a comprehensive international review of STEM education is beyond the scope of this paper, we would argue that the framing for this position paper may transcend the geopolitical boundaries of educational settings (Wagner et al., 2020).

The global pandemic has made data reasoning ever more important. It also opened up new modalities for learning online where students have access to greater sources of knowledge and learning. At the same time, the pandemic laid bare deep existing inequities within the U.S. and international educational systems (Brodie et al., 2021). The "digital divide" became more apparent than prior to remote learning and even as U.S. educators raced to put laptops into the hands of students, the access, experience, quality, and quantity of education varied widely (Lee & Campbell, 2020; Walters, 2020).

Currently, numerous indicators, including general U.S. K12 STEM participation and achievement, post-secondary STEM enrollment, conferred STEM degrees, and STEM career attainment, show that the majority of those who engage in STEM are male, white or Asian, and middle to upper economic class (McGee, 2020; Morton & Riegle-Crumb, 2019; National Science Foundation & National Center for Science and Engineering Statistics, 2017; Riegle-Crumb et al., 2019). This is a systemic, multi-dimensional issue, not due to individual choices. With data showing that the lack of broad participation is a persistent trend, the pathway for diverse STEM employment will remain limited if STEM education does not start to shift the perception of who is capable of engaging in STEM.

Leaders in industry and education struggle to increase the diversity of those engaged in STEM. There is a chronic absence of diverse STEM leaders working with diverse youth who are racially, ethnically, and linguistically insiders in that community. Without diverse educational STEM leaders, practices, can emerge that may cause historical, cultural, and curricular damage, further alienating diverse learners and communities from seeing themselves as scientists, technologists, engineers, and mathematicians (Ighodaro & Wiggan, 2011; Philip & Azevedo, 2017). STEM education and educators must create opportunities in which diverse youth see that their contributions matter and that STEM is not a discipline limited to narrow sets of procedures unrelated to the real world, or for a privileged few.

We must reposition diverse community educators as central to co-creating STEM learning opportunities for diverse youth.

Central to creating innovative STEM education serving diverse learners is working in partnership with communities, breaking down barriers of knowledge production, and all educators doing the work to check their implicit bias about who is capable and what is STEM. Scholars warn it is imperative that STEM educators, especially but not only white educators, working in minoritized communities examine their motivations for engagement and recognize the historical legacies of assimilationism that have resulted in the erasure of diversity of thought and ways of being (McGee, 2021; Milner, 2020). With the recognition of systemic inequities, educational equity is achieved *only when* we no longer can predict participation and achievement in education or careers of youth based on their social characteristics, i.e., race, socio-economic status, primary language, gender, or physical or intellectual abilities (Gutiérrez, 2012). To work toward equity, we must act to dismantle the unjust barriers in educational systems, including the exclusionary STEM culture and narrow definitions of what counts as STEM, so that diverse youth are proportionally represented across STEM pathways and careers.

Broadening the participation of diverse, Black, Indigenous, and People of Color (BIPOC), in high-technology jobs can drive innovative solutions that positively impact diverse communities (McGee, 2021; Muro et al., 2018) and possibly disrupt a disturbing trend of technologies increasingly being used to monitor these communities (Benjamin, 2019). The Pew Research Center (2018) and others have reported that although women are employed in close to 50 percent of jobs in the U.S. economy, they hold fewer than 25 percent of STEM jobs (Beede et al., 2011). Research on U.S. STEM workforce development shows that from 2000 to 2015 high-tech jobs grew nearly three times the rate of non-STEM jobs (Noonan, 2017). Increasing women and diverse learners' participation in STEM and their access to careers is vital for STEM innovation. Dissecting the reasons *why* current STEM employment isn't diverse is beyond the scope of this paper; rather, we raise these issues to point out the systemic nature of the problem and the need to work on shifting STEM educational opportunities for diverse youth to impact the workforce of the future.

International STEM informal education research has documented approaches that break barriers to diverse communities' STEM participation. Some promising practices have taken place in hybrid spaces outside of schools, such as camps, clubs, and programs associated with community-based organizations (Archer et al., 2021; Booker & Goldman, 2016; Carlone et al., 2016; National Research Council, 2015). Research on informal learning has suggested that when youth develop STEM interests and identities via hybrid spaces they are more likely to weather some of the persistent STEM barriers in schools and persist in their STEM interests (McCreedy & Dierking, 2013; Shaby et al., 2021). These innovative programs can help diverse youth develop interest-based questions, experience opportunities for leadership, and work collectively toward solutions (Krishnamurthi et al., 2013; Philip & Azevedo, 2017).

Not all informal learning spaces are created equal, and not all serve diverse youth (Godec et. al, 2021). Thus, it is important to employ learning designs that value physical, social, cognitive, and emotional engagement that can legitimize youth as authors of STEM knowledge (Bang & Vossoughi, 2016; Durall et al., 2021). Solving physical and conceptual problems rooted in needs and context provide a sense of competence and identity as a part of a community (Marin & Bang, 2018). Further, these designs support the emergence of STEM identities, disrupting traditional views of who does STEM and what doing STEM looks, sounds, and feels like. Such educational innovations are found in numerous STEM areas, from field ecology to data camps for girls (Carlone et al., 2015; Craig et al., 2011). With careful considerations of design, researchers with minoritized youth have documented promising opportunities for youth to author STEM ideas, harness STEM tools addressing interest-driven questions, and build STEM knowledge and practices (Bell et al., 2017; Lee, 2017; Rahm, 2019). As a result of such experiences, youth see themselves as scientists, innovators, and engineers.

3. Breaking barriers with transdisciplinary STEM participation

The world is experiencing a data revolution that dramatically impacts our everyday lives and how we create new knowledge and innovate (Cinnamon, 2020; Gray et al., 2018; Kitchin, 2014). To address how data are used globally and locally in both productive and non-productive ways, we need data literate community members who can decipher valid arguments when bombarded with seemingly well-justified perspectives. The potential impacts of the data revolution drive an urgent need for diverse youth to build their data literacy and geospatial reasoning. When youth are empowered to pose questions about their community, draw upon multiple sources of data that link to features of the community, and leverage resources (i.e., people, tools, information), they are well poised to make sense of situations in innovative ways and imagine creative solutions not necessarily governed by traditional narrow views of disciplines and hierarchies of who has the power to act on their world.

We advocate for leveraging 21st-century mobile technologies to develop STEM reasoning because of the widespread availability of application-based, wearable technologies that can build geospatial awareness and integrate historical and other place-based knowledge (see, e.g., Hall et al., 2014; Lee & Shapiro, 2019; Hsu et al., 2020; Open Street Maps, n.d.). Mobile devices have been shown to break down barriers to access, narrowing the economic digital divide (Rubel et al., 2017). Within the U.S., 84% of teens have a phone, and 53% of youth by age 11 (Common Sense Media, 2019). Previous studies have shown that technology access is nearly equally distributed across genders and those who identify as Hispanic or white (Lenhart, 2009). With this widespread growing availability, mobile technologies offer an economically viable and motivationally enticing vehicle for advancing diverse youth STEM learning opportunities.

Equally essential is considering how technology can obscure geospatial reasoning and the need for embodied opportunities to investigate and build spatial awareness (Bryant & Frazier, 2019). Tools such as physical maps can assist in the development of geospatial reasoning via orienteering, geocaching, map making, and other geospatial-oriented activities, thus expanding opportunities and access to STEM learning. Developing geospatial learning opportunities adapted to the local needs of learners and technologies is essential to breaking barriers to geospatial reasoning. We advocate customizing tools that integrate technologies and embodied opportunities for youth to develop geospatial reasoning. Across these mediums, diverse youth will be able to create and investigate data, drawing upon transdisciplinary forms of STEM knowledge and practices in ways that benefit them, their families, and their communities (Benjamin, 2019).

Data literacy and geospatial reasoning are foundational to expanding what, how, and where STEM learning happens. By *data literacy,* we mean the ability to *read, write, and communicate* in the data-rich world by making sense of issues and questions using data, understanding data production, critically analyzing situations and identifying tools to address them, and making evidence-based inferences and arguments to address a problem while recognizing the limitations and context from which data were produced (Bargagliotti et al., 2020; NGACBP & CCSO, 2010; NRC, 2013; Rubin, 2005; Vahey et al., 2012). By definition, data reasoning is iterative and involves feedback loops so that models and solutions can be revised and adapted as new assumptions and evidence are brought to light (Lipman, 2010). *Geospatial reasoning* is a form of reasoning that draws upon concepts about space (e.g., dimensionality, continuity, proximity, and separation) and tool use (National Research Council, 2006). Data literacy and geospatial reasoning concepts link STEM concepts to youths' communities and lives, thus shifting images of what it means to do STEM and where STEM happens (Brunner et al., 2021; Calabrese Barton & Tan, 2010; Caspe et al., 2018; Lee & Shapiro, 2019).

National and state education policies in the U.S. have identified the need for youth data literacy opportunities (e.g., Boaler & Levitt, 2019; Daro & Asturias, 2019; Koh, 2020; Matthews, 2019) and geospatial reasoning (National Research Council, 2012; 2013) to be infused into formal education. These policy documents emphasize transdisciplinary, technologically-innovative learning. Yet, research on youths' statistical literacy, a key construct contributing to data literacy, suggests that it remains marginally developed in school settings (Lehrer et al., 2014; Tarr et al., 2006). Policy efforts calling for the infusion of geospatial reasoning have seen limited success in school settings due to a focus on other content, teachers limited knowledge base, and limited access to technologies and data sources (Hammond et al., 2018, 2019).

This limited focus on statistics and geospatial reasoning in school is one rationale for studies and grant-supported efforts in informal education (e.g., Bodzin et al., 2020; Schlemper et al., 2018; Rubel & Nicol, 2020). These studies focus on developing STEM interests or attitudes and position youth to ask questions relevant to them in ways that leverage data literacy and geographical information systems (GIS) (Kahn, 2020; Lee et al., 2021; Lee & Shapiro, 2019; Rubel et al., 2016a; Taylor, 2017; Taylor, 2020; Taylor & Hall, 2013; Wilkerson & Laina, 2017). Many of these investigations use representational tools, like GIS technologies, that can facilitate the collection, management, analysis, and visualization of data, providing tools for youth and families to pose interest-based questions and frame solutions.

4. Breaking barriers with participatory design

Many of the studies on data literacy of diverse youth using geospatial reasoning uncover the tensions of working within educational systems situated within diverse communities and attending to diverse youth interests (e.g., Enyedy & Mukhopadhyay, 2007; Philip et. al., 2016; Rubel et al. 2016b; Wilkerson & Polman, 2020). However, the transdisciplinary context of participatory design that blends ideas from informal learning design principles, participatory design research with participatory community science has proven to break down barriers to STEM participation for youth and families (Bang & Vossoughi, 2016; Booker & Goldman, 2016; Coenraad et al., 2019; Durall et al., 2021; Tzou et al., 2018). These studies position youth, families, other community members, and researchers in a partnership that rejects typical hierarchies of *knowledge,* designs for *learning*, and the design and reporting of *research* (Bang & Vossoughi, 2016; Penuel, et al., 2020).

For the past 20 years, engineering education settings have included attention to the user during design and moved to connect designers and the community via service learning (Oakes, 2004). User-centered design has included (but not limited to) human-centered design (Bødker & Kyng, 2018; Marsden et al., 2008; Meyer & Norman, 2020), evidence based-design (Lippman, 2010), and industry-sponsored design projects in educational settings (Okudan et al., 2006). For the last decade, design thinking sensibilities and engineering practices have been integrated into U.S. K12 education policy (Katechi et al., 2009; NRC, 2013). Many of these approaches involve the integration of resources (people, tools, and ideas) in the scoping of problems, identifying potential assumptions, partnering with users to identify community projects, and building solutions. While these policies offer opportunities to integrate STEM education and professional engineering practices there are shortcomings in these approaches due to the hierarchy of roles (designers maintain an expert position) or the interests of different genders or disciplines (Günay et al., 2020; Okudan & Mohammed, 2006). Without explicit attention to the power dynamics of these approaches and intentionality to examine what is perceived as STEM disciplinary practices, we risk perpetuating persistent educational inequities (Agarwal & Sengupta-Irving, 2019; Philip & Azevedo, 2017).

Through partnerships, we see the potential for unleashing creativity and innovation as envisioned in human-centered design and design thinking (Kelly & Kelly, 2013) and confronting the divide between designers and users. This collaborative effort repositions all partners as designers in the process of question-posing, solution ideation, prototyping, and testing evidence-based ideas (Corburn, 2003; Bonney et al., 2016; Loh & Kim, 2021). As a result, we elevate youth authority and cultivate a community's transformative agency (Booker & Goldman, 2016).

Researchers engaged with participatory approaches attend to *who* has access and power in learning and *what knowledge* is privileged historically and currently. In STEM, this means interrogating and shifting who is seen as capable, whose knowledge is valued, and what practices are central (Coenraad et al., 2019; Penuel et al., 2020). This critical perspective allows for a (re)positioning of minoritized youth and families as central in STEM. It means broadening definitions of STEM domains and who is capable of facilitating STEM learning. We propose a framework for informal learning (e.g., community organizations, after-school programs, and other youth-serving spaces) as settings for taking up our design considerations. We posit that data literacy and geospatial reasoning are well-suited for a participatory approach because they are accessible, connected to everyday life, and relevant to diverse multigenerational communities. We advance a participatory approach to data literacy and geospatial reasoning by taking up place-based STEM questions formulated by youth, families, and their communities to impact them and the world (Caspe et al., 2018; Gutstein, 2006; Moses & Cobb, 2002).

5. Transdisciplinary framework for participatory STEM education serving diverse youth

The framework guiding our thinking for transdisciplinary STEM education draws on the expertise of the authors of this article, leveraging the complementary disciplinary, professional, and personal, educational histories of international and U.S. contexts. Our partnership grew as we worked across boundaries, negotiating a hybrid space to begin building understandings of different terminology and disciplinary language, disciplinary practices, and core ideas informing learning opportunities. As we brought respective areas of expertise to bear on how to support diverse youth and family STEM learning, we found that we had to define and justify our ideas to one another and open ourselves to new and fresh perspectives from others. We found convergence on a set of ideas from these discussions, not rooted in any one discipline. We view this convergence framework as a transdisciplinary boundary-spanning object for engaging diverse youth. Positioning this framework in the informal learning setting creates a liminal space for youth, families, community organizations, university educators, and researchers between formal learning spaces and everyday learning (Thomassen, 2016). Outside the confines of formal education, we can reimagine agency and structure, spark innovation, and creatively consider new possibilities of not what *is* but what *can be* (Greene, 1986; 2010).

This participatory-design framework focused on increasing data literacy and geospatial reasoning leverages linkages between learning and identities. We propose an interest-driven, place-based, community-centered framework that engages a wide range of participants to do STEM and experience the world as problem-solvers. As a result, learning takes place in the context of a partnership of youth, families, and community-based organizations in which diverse youth may realize STEM identities. In this vision, youth and families bring knowledge and practices vital to STEM education, and their participation shapes the tools and discourses of STEM disciplines as STEM disciplines shape their involvement.

5.1. A transformational STEM education vignette

To give a sense of the STEM education we envision, we provide a glimpse into a transformational STEM program situated within a community organization. Though the scene is imaginary, the setting is real: a bicycle shop in Southwest Detroit that has been a gathering place for youth for many years. The shop offers free bicycles to students who use them to travel to work and has become a magnet for neighborhood youth of all ages. This is an ideal setting for expanding STEM learning opportunities to youth in this neighborhood. Imagine that a nearby community center partners with the bike shop to offer bike mechanic classes to support local youth. Through these classes, youth talk about mobility in the neighborhood and have noticed that bus routes in the area have changed. They discuss that more bike lanes are needed to ensure safe bike commuting to school and work. In addition to impacting the youths' transportation, these changes in public transit have impacted their families' access to work, school, shopping, and visiting friends and family members. Along with the community center educator, the group of about ten middle school-age youth who regularly visit the bike shop after school start posing questions about these changes and decide to investigate why changes were made and what were the resulting impacts on their community.

The community center leader, a former youth from the neighborhood, supports the group in thinking about these changes in the historical context of Southwest Detroit, community resources, and how youth might build evidence for safe bike commuting routes and their families' mobility needs. The youth and the leader collect knowledge of the community and insights they have developed from years of living and commuting. Collectively, they find ways to represent their community via images and maps in order to decide what additional information is needed. As they decide on ways to collect new evidence to contribute to the collective mapping of the community, the community center leader guides them to use mobile tools accessible while on their bikes to observe bus ridership, and map existing bike lanes and road conditions that impact bike safety and accessibility. The youth speak with community members about their needs, and create maps to indicate where current bike lanes and new bus routes intersect. They also decide that they need more than just their needs served and survey to find out what are families' common bike and bus commutes in the area.

The youth, in partnership with the community center leader and bike shop owner, enlist family members and local university partners who offer technological tools such as GIS and other resources to help them coordinate data, analyze the data spatially, and uncover what bike lanes and bus routes are most used and needed, taking into account needs of different users and their mobilities. With the support of their families and the community center leader, the youth use these data as the basis of a presentation to city leaders to gain support for allocating more resources to mobility needs based on their analysis of the evidence they have gathered in collaboration with their families and other community members. The youth realize this is a temporary solution. As the community's needs change, they will need to refine their solution based on the analysis of new evidence. For now, their model solution for proposed bus routes and bike lanes is a good start; it provides the needed assurance that bikes and buses can safely share the road and that community needs can be better met with active, collaborative engagement using STEM and other tools.

5.1.1. Reflection on the vignette toward a framework for STEM education

This transdisciplinary, interest-driven experience gives youth the opportunity to formulate their own questions about mobility (i.e., bike lanes and bus routes) and the ways in which the neighborhood members can collect and use data to construct a persuasive argument. Youth, with their family members and other trusted adults in the community, expand their data literacy through their investigation, reporting, use of GIS-based tools, and application of analytic resources. Further, the youth frame what is the evidence needed to shape access to resources, fostering their agency and demonstrating their authority. Finally, they hone their communication literacies with community stakeholders to contribute to their community.

Five intertwined design considerations shape the kind of transformational STEM learning that we are posing in this aspirational vignette (see Fig. 1). First, STEM learning is propelled by youths' interest-driven, place-based learning rooted in community issues and advocacy for solutions. Youth, immersed in their community and working with their families, initiate investigations relevant to themselves and their neighborhood. Second, the STEM learning that takes place builds upon the interests, expertise, and

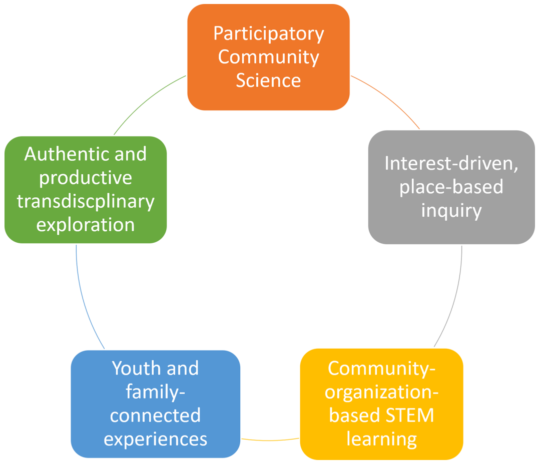

Fig. 1. Framework for Transformational STEM Education.

assets of community organizations. The third consideration in this learning process is youth and their families are recognized as experts on community needs, assets, and how to advance new knowledge. They assert agency by accessing knowledge, tools, and resources needed to address their needs. A fourth design consideration is the authentic and productive disciplinary learning of STEM knowledge and practice – posing evidence-centered questions, data collection using geolocation technologies, data analysis, data representations, and communicating a data-based story – involving rigorous, authentic, and transdisciplinary STEM. Fifth, this vignette provides an example of participatory community science, where youth and their families engage in and contribute scientific knowledge working on behalf of their own community.

What can be the expected outcomes of this kind of educational experience? Through their investigation of transportation, the youths and family members assert and enhance their STEM identities and interests. That experience, in turn, leads to expanded access and participation of diverse youth and adults in STEM fields. While it may not be directly thought of in terms of doing STEM by the youth and families, since the activity is a community-centered civics project, it provides an opportunity for the STEM leaders and educators involved to communicate aspects that are components of STEM careers.

Design considerations and expected outcomes of our proposed framework for transformational STEM education are shown in Fig. 1. The theoretical concepts and research underlying the design elements of our framework for designing transformational STEM learning opportunities and expected outcomes are discussed below.

5.2. Transformative STEM education design considerations

5.2.1. Immersive, interest-driven place-based learning: The role of space and place

A crucial design dimension to our framework is a place-based approach to reinforce learners' sense of ownership over the purpose of their learning. Interest-based learning drives the focus of youth and family investigations based on needs and issues authored by youth and rooted in youths' communities, families, and community-based assets (Marin & Bang, 2018).

People perceive space differently based on their background and lived experience (Lefebvre, 1991, orig. 1974). People with different characteristics take up more and less space, move through space differently, and feel more and less comfortable in different types of public and private spaces. Youth, especially BIPOC youth with limited economic resources may feel that their "right to the city" or place is in doubt (Harvey, 2008; Henderson & Jefferson-Jones, 2020). However, these same youth are often already experts on *their* neighborhoods' dynamics, connections, anchors, and inhabitants. Immersed in their local environment, youth can formulate relevant and meaningful questions to explore based on their own spaces and expand their sense of place and authority. From a human-centered design point of view, youth will have knowledge and experiences to empathize, define, ideate, and prototype (IDEO, 2015). In our vignette, the participants claim a right to be served by their city's transportation system in a way that allows them and their families to move around the city to meet their needs.

5.2.2. Community organization-based STEM learning: Community expertise, interests, and assets

A second design dimension of this framework is building community partnerships or joining established community partnerships within minoritized communities led by community members. Designs for community-centered, interest-driven efforts would need to emerge collaboratively, drawing upon the expertise of the informal educators working with their community members. Collaborations can emerge by connecting to youth-serving community spaces. Working with local and national youth development groups, including career development programs (e.g., the C2 Pipeline at Wayne State University, https://c2pipeline.wayne.edu/), STEM-centric youth clubs (e.g., Science and Math Investigative Learning Experiences at Oregon State University, https://smile.oregonstate.edu/), community centers serving youth, libraries, and summer camps (e.g., bike collectives, youth athletics organizations, youth media/data camps, environmental centers, and community gardens), or national youth leadership programs (e.g., scouting or 4-H Youth Development at Iowa State University, https://www.extension.iastate.edu/4h/), can bring expertise in the cultivation of interest-driven spaces for youth and families and connections to community assets. Empowering youth by leveraging community resources for learning is within the missions of these organizations. In these settings, we imagine participants and leaders co-creating tools and activities that aid in youths' interest-driven questions and innovative design (Altavilla et al., 2021; Kelly & Kelly, 2013). This design work involves taking up youths' and families' social and cultural repertoires of practice, valuing their ways of knowing and engaging (Gutierriz & Rogoff, 2003). In our example vignette, the bike shop already a community gathering place shaped by and responsive to local social and cultural practices becomes a space for such learning.

Leading youth learning in community organizations centered on community-based problems that draw upon geospatial reasoning and data literacy requires significant STEM knowledge and knowledge of learning. Leaders must have artful and understated ways of leading that orchestrate opportunities for learners to engage with their uncertainties associated with problems, leverage resources in response, draw upon disciplinary and cultural repertoires of practices, and cultivate agency (Agarwal & Sengupta-Irving, 2019; Engle & Conant, 2002). How does an educator lead so that youth drive the learning? When to step forward, and when to step back so that youth propel the work and benefit from the collective knowledge of the group? At what critical junctures are STEM practices and concepts introduced? Models of this kind of facilitation exist and we acknowledge the significant and ongoing investment required to cultivate this set of facilitation skills, knowledge, and dispositions (Elliott & Lesseig, 2022; Forman et al., 2014; Lewis, 2016). This effort represents a departure from traditional models of teaching in formal settings; this kind of leadership can draw upon aspects of what formal teachers do; this kind of facilitation can also shape, in positive ways, what teachers do in formal settings.

Much of the STEM education framework that we promote depends on cross-sector partnerships. Partnerships are vital to take stock of community assets and stories that highlight how community members use their community and communicate within it (Krishnamurthi et al., 2013). In some communities, this may be within community centers or libraries that offer space for youth to engage in afterschool or summer programs, where they identify a need that involves data-driven solution generation tied to geolocation. These experiences would need to be high interest, engaging, and relevant to draw in youth and families. The outputs of these efforts (i.e., new designs, products, persuasive presentations, and solutions) would need to be shaped by the needs of the community through their unique social and cultural practices. (Gutiérrez & Rogoff, 2003). We see this as the first step to building awareness of geospatial tools with a clear commitment to (re)positioning youth and families as STEM knowledge scientists, engineers, and leaders broadening the definitions of who does STEM and what STEM is. Such design efforts lead to transformative agency (Agarwal & Senguta-Irving, 2019; Booker & Goldman, 2016).

5.2.3. Youth and family partnerships to advance STEM learning

A third design consideration in this transformational framework is family-connected STEM learning. Early adolescence is a crucial time in the development of youths' STEM identities, shaped by their interests, perceptions of themselves, and family interests and careers (Ishimaru et al., 2015; Oymak, 2018; Wyss et al., 2012; Watt et al., 2017). While research shows that youths' career-related interests and educational aspirations are influenced by a myriad of factors, families, especially mothers, play a large role in youths' stated influences (Oymak, 2018; Watt et al., 2017). Learning opportunities that strategically involve families (or those with close, family-like ties) in youths' learning experiences and that take an asset-based approach to families' STEM expertise can reposition how youth see themselves as STEM scientists (Caspe et al, 2018; Nugent et al., 2015). Considering our vignette, when youth work to address community-based problems, their families offer deep expertise for understanding the history and scope of a problem, its impact on the community, and through collaboration they can provide information and other resources to design solutions. We see opportunities to engage youth with intergenerational family learning as necessary because of the impact families have on influencing youths' interests and creating images of what is possible in terms of future education and careers (Knapp et al., 2017). We understand that family influence is not deterministic, rather it is one of many influences that shape how youth develop interests and construct STEM identities.

5.2.4. Authentic and productive transdisciplinary exploration

Authentic and productive transdisciplinary exploration is a fourth design dimension in our framework. Authority and agency of learners are central in this design dimension (Engle, 2012). Thus, the authority of youth and families to author questions, identify needs, and call for learning resources exemplify this dimension. For authentic learning to take place, youth need opportunities to encounter the uncertainty associated with authentic scientific and community-situated questions. They also need opportunities to connect and leverage resources framed by STEM disciplines, socio-political/community contexts, and their own cultures, identities, and histories (Agarwal & Senguta-Irving, 2019). When youth, families, and community members collectively create evidence-based solutions to community-based problems, they have opportunities to shape solutions to their needs and choices as they bring to bear new and existing disciplinary practices of STEM (Engle & Conant, 2002).

Authentic learning is social, mediated by culture and tools. These tools are material, such as GIS technologies and mobile devices, analytic tools such as mapping, spatial reasoning, and quantitative reasoning, and relational tools such as communication with community-based leaders, others with expertise, family members, and peers (Nasir & Cooks, 2009; Wertsch, 1994). Tool-mediated authentic learning is the process of participation in a community through disciplinary practices. Authentic and productive transdisciplinary exploration is a process of leveraging established community practices and the capacity to transform the community practices through collective agency (Gutiérrez & Rogoff, 2003).

5.2.5. Participatory community science: Generating STEM knowledge

The fifth dimension of our framework is participatory community science. Participatory community science is a means for generating scientific knowledge via community members' data collection, analysis, and solution generation, recasting scientific knowledge as something created by all community members and not isolated within an elite profession. Community science, also known as citizen science, has a long history of involving community members across generations, levels of expertise, and educational backgrounds to contribute to solving scientific questions through crowdsourcing data collection for research. We emphasize the more inclusive term "community" to consider community science as a process by which knowledge generation hierarchies are broken down (Loh & Kim, 2021).

Research on participation in community science documents the benefits of being involved in science, especially for those who might otherwise not participate (Bonney et al., 2014; Cashman et al., 2008; Corburn, 2003). The place-based approach and involvement of families in community science positions science as something that everyone can participate in and that is relevant to a community's concerns (Bonney et al., 2016). Through identifying problems, collecting and analyzing data, and proposing solutions, community science provides youth and families with tools and expertise to advocate for and improve the communities where they live and go to school (Corburn, 2003; Strasser et al., 2019). For example, community science has been applied across a diverse set of science contexts using Geographical Information Systems Science (GIScience) including marine and land animal ecology, community resiliency planning, and urban planning (see e.g., Dixon & Johns, 2019; Corburn, 2003). Urban planners use public participation GIS specifically to "promote the inclusion and empowerment of marginalized or underrepresented populations in the development and use of spatial information" (Brown & Kyttä, 2014, p. 125) to be used in situations from community asset mapping to local land use decision-making (Schlossberg & Shuford, 2005).

Community-based participatory research (CBPR), or participatory design research (Bang & Vossoughi, 2016; Penuel et al., 2011), has participants co-design an inquiry, contribute to data collection, and collaborate in the analysis, interpretation, and reporting of findings (Cashman et al., 2008). A major challenge of a CBPR approach to GIScience lies in making the GIS technology accessible enough for participants to use without error or frustration (Newman et al., 2010). Similarly, in education contexts, participatory design research studies enlist youth as data journalists and historians to tell geolocation data stories of communities using youth-driven questions with accessible technological tools for data collection and analysis (see e.g., Taylor, 2020; Williams et al., 2014). Analytic tools aligned to task, needs, and expertise is critical to breaking down barriers to accessibility, redistributing who has the agency to solve problems, and empowering youth as designers (Aboutajedyne et al., 2021; Lee et al., 2020).

Although GIS products such as ArcGIS have become considerably more user-friendly over the years, especially as they have moved toward web-based user interfaces, they still work better for users with significant GIS experience. As a result, technologists have partnered with educators, researchers, and scientists to develop tools that are accessible to youth and others so that interest-driven questions may be pursued. Many of these partnerships have been grant-funded or in collaboration with highly-specialized, university-based labs (see e.g., Rubel et al., 2017). Similarly, analytic platforms have been developed that support "low floor" entry such that analytic tasks are accessible and the interface is more intuitive, especially for digital native youth, familiar with navigating mobile applications (see e.g., The Concord Consortium, 2021). We see these efforts as promising for breaking barriers to access and broadening who generates STEM knowledge in data literacy and geospatial reasoning. Thus, there is a benefit for a community science that is participant-driven, inclusive, and rigorous in its approach to GIScience providing tools that are easy for an inexperienced learner to use. We also recognize there are limitations to this approach and address this in our discussion of framework limitations.

5.3. Expected transformational outcomes

5.3.1. Development of interest in STEM education

An outcome of engagement in this transformational framework is the development of youth interest in *doing STEM*. Researchers define interest as a predilection of individuals to re-engage, over time, across settings, with particular disciplinary content shaped by interaction with environments (Hidi & Renninger, 2006; Krapp, 2007; Renninger & Hidi, 2011). Youths' interests emerge over time and across settings within activities where they draw on available resources, people, practices, and situational environments. The implication of this interest conception means that productive youth experiences with geospatial reasoning need to provide adequate resources, access to youth-relevant problems, create rich space for youths' authority, and engage in authentic practices of the discipline (Engle, 2012; Carlone & Johnson, 2007; Tan & Calabrese Barton, 2020). Researchers of youth STEM interest posit that interest emerges both in formal and informal settings and that it is important to not only gauge if youth "like" a topic, but to track what youth learn, the type and extent of social support (human and material) for their interest, and the value they associate with a topic (Falk et al., 2016). A successful outcome from prospective projects drawing upon this proposed framework would be increased STEM interest that is durable, positioning diverse youth to pursue their aspirations with expanded power.

In addition to interest, another outcome is enhanced STEM identity. Interest and identity, while related, are different. Identity involves both seeing oneself as a member of a community and feeling welcome and capable to engage in the practices of the community (Hand & Gressalfi, 2015). Informal learning settings are important spaces for youth to cultivate identity and agency. Informal educational spaces do not include many of the boundaries that formal educational spaces do (Hull & Greeno, 2006; Penuel et al., 2016). Tracing STEM identity over time would be an important marker of successful projects informed by the dimensions of the proposed framework.

Holland and colleagues (1998) frame identity development within social, cultural, and political spheres they call "figured worlds." This perspective on identity examines the ways that youths' and families' social and cultural practices of their varied figured worlds are valued or not valued. This conception of identity realizes the history and power of cultural practices to include or exclude actors by essentially communicating that "people like me" do or do not participate in particular practices (e.g., hobbies, sports, disciplines, occupations, and domestic tasks). Youth and family members can develop and take on new positional identities by engaging in new practices and discourses of new communities. They may also bring forward different practices from their varied figured worlds to reshape the practices of a community.

We advocate tracing youths' and families' geospatial reasoning and data literacy identities by documenting the overlapping cultural practices from their varied figured worlds, the ways that they express their positional identities, and the insights they share as they identify and solve community-based problems using geospatial reasoning and data literacy. We may better understand those who are served by designed environments and what processes afford or hinder authentic productive transdisciplinary engagement by tracking how youth and family members participate, what type and extent of support (human, material, and social) is leveraged, and how youth and families narrate themselves in relation to these constructs (Falk et al., 2016; Agarwal & Sengupta-Irving, 2019; Tan & Calabrese Barton, 2020). Measures of STEM interest (see, e.g., Falk and colleagues) and qualitative measures of identity and engagement (see e.g., Nasier & Cooks, 2009; Tan & Calabrese Barton, 2020) are most appropriate to adjust and improve projects using this framework. In addition, examining the emerging interest and agency of youth and families is crucial in participatory community science and in projects informed by the dimensions of this framework.

6. Limitations and further considerations of this framework

While we are optimistic that the transformative framework described above can overcome some traditional challenges of broadening STEM education, we acknowledge that it introduces significant challenges and limitations. First, this approach depends on cultivating partnerships within diverse communities focused on designing solutions to community-based problems. We see community organizations as key to developing these partnerships because they are rooted within communities and generally focused on building capacities with communities. We also recognize that not all community-based organizations have access to and capacity with technology that may be needed to address the community-based problems. As a result, we advocate for customization to local needs and leveraging mobile technologies, such as applications that can be accessed via phones and other low-cost devices, because of their ease of use and the ways that youth's expertise as "digital natives" can be elevated and leveraged. Through the use of mobile technologies and other analytic tools, diverse youth may be empowered with skills and competencies transferable to high-tech degrees and careers.

Second, developing a mobile application for geospatial data collection and analysis easy enough for GIScience novices to use but powerful enough for meaningful analysis will require resources. A mobile application would require funding and likely an industry partner for development. Numerous committed community and educational partners will be needed for testing, validation, and collaboration. This approach is ambitious in the level of scientific effort and engagement necessary for success. While such engagement is beneficial, it will be important to strike a balance between making any such learning experience attractive and fun, providing learning opportunities centered on data literacy, geospatial reasoning, GIScience concepts, problem solving, *and* advancing youth and family interest-driven questions and designs. Buy-in and technical savvy from youth, families, community partners, and university members will be in high demand when each actor must also be engaged in their respective prior commitments.

When youth interest drives STEM learning, a great deal of care and intentionality is required to ensure that youth have a comprehensive and cohesive STEM experience (Rubel et al., 2016a). When knowledge generation and learning are driven by youth, families, community members, and university-based members this demands that all stakeholders make a commitment to negotiate and persist with one another. These are not qualities easily cultivated nor typical in educational innovations (Bang & Vossoughi, 2016), thus these challenges are not to be taken lightly. We see promise in working within informal educational settings, because of the learning context that is less rigid and policy-driven by federal and state accountability assessment practices. Long-term, sustainable partnerships among community members, youth, community organizations, and outside expertise must be cultivated to allow for distributed expertise and trust-building.

Likewise, it will be important to get the pacing right. Going too slowly, youth may be disinterested. Moving too quickly could mean that the development of STEM identity is thwarted by participants' confusion or anxiety. As mentioned earlier, high-quality facilitation is required to allow youth to drive their own learning, pose questions of interest to themselves, draw in families, and make community connections in ways that allow learners to take the lead (Elliott & Lesseig, 2022; Forman et al., 2014; Lewis, 2016). Projects informed by this framework also will need to shift the perception that learning is fast and automatic. In this framework, learning is iterative and proceeds at a pace set by youth, their interests, and engagement.

Along those same lines, it will be important to figure out ways to bridge in-school STEM learning with these hands-on and interactive ways of knowing, in order for youth to see themselves as "the kind of people who do this stuff." Many community organizations and after-school programs are facilitated by certified teachers, who teach school as a part of their "day job." These educators offer a bridge to school and its possible transformation. Further, recent shifts being made in U.S. STEM policy, namely standards that value connecting STEM to real-world problems, less focus on endless lists of content to cover, and reduced focus on accountability assessments are positive changes that are supportive of the proposed framework for STEM education. As these policy changes take root, educational practices guided by informal learning principles like those in this framework may become more present in schools. Teacher education and professional development programs for formal and informal educators will be essential to scale the implementation of the transdisciplinary STEM (content and instructional) practices consistent with our framework.

Ongoing formative and summative evaluation will be vital for projects informed by this proposed framework. Evaluation would need to track youth's perceptions of the activities, capacities of projects to take up multiple perspectives across stakeholders, distribution of data literacy and geospatial reasoning expertise, and the sustainability of partnerships. We advocate for using methods that trace outcomes such as youth's and communities' STEM engagement, STEM interests, and emerging STEM identities including expanded expertise. Such methods would likely include the use of multiple observational protocols, analysis of design products, interviews, and surveys. The aim of this constellation of measures would provide project partners with ongoing and retrospective evaluations of project effectiveness.

7. Conclusion

In this position paper, we identify leverage points for a new place-based community science approach to STEM education. Drawing upon extant research across our teams' fields of expertise, we argue that a transdisciplinary framework is necessary to address barriers in our current educational system and imagine beyond those boundaries what has not yet been made possible (Greene, 2010). We believe this *proposed* framework has the potential to overcome some of the persistent challenges to broadening STEM education and subsequent STEM careers for diverse youth. We argue that an interest-driven, place-based approach that leverages partnerships among youth, families, and community organizations can lead to authentic and productive transdisciplinary STEM learning. When youth have opportunities to identify locally relevant problems and investigate them through geospatial technology, data literacy, and design-based problem solving to propose persuasive solutions, they will increase their STEM knowledge, have an expanded sense that STEM is relevant to their life, and develop robust STEM identities may shape their community and their future.

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Carolyn G. Loh is an associate professor of Urban Studies and Planning at Wayne State University. A former practicing planner, she studies local land use decision making, comprehensive planning, arts and cultural planning, and diversity, equity, and inclusion in planning and plans. She has taught courses in Geographic Information Systems and urban geography for more than a decade. She has recently written about how a community science approach could benefit planners and planning researchers.

Carolyn E. Psenka was raised within a family of engineers and artists, educated in business, and experienced as a public accountant before receiving her Ph.D. in cultural anthropology. As an applied anthropologist, she has studied knowledge sharing and information technology in large scale aviation, aerospace, manufacturing, and medical systems in private and governmental contexts. Her current research is concerned with understanding the relationship of technology, culture, and the participation in families and communities in STEM learning.

Jennifer M. Lewis was an elementary and middle school teacher for ten years before earning a doctorate and joining the faculty at Wayne State University. She has recently returned to her position as associate professor of mathematics education and teacher education at WSU after a leave of absence to serve as the Executive Director of Educator Excellence in Detroit Public Schools Community District. Jenny's research focuses on how teachers learn mathematics during instruction. She is particularly interested in building systemic efforts to improve mathematics teaching and learning in high-poverty communities.

Kyoung-Yun Kim is a professor in the Department of Industrial and Systems Engineering at Wayne State University, where he directs the Computational Intelligence and Design Informatics (CInDI) Laboratory and Smart Manufacturing Demonstration Center (SMDC). Dr. Kim is a site director of NSF I/UCRC Center for e-Design. Dr. Kim was the lead PI of the NSF CooL:SLiCE (Constructionism in Learning: Sustainable Life Cycle Engineering) project. Dr. Kim's research focuses on design science; design informatics; semantic assembly design; welding and joining; and smart manufacturing.

Karl R. Haapala is an associate professor in the School of Mechanical, Industrial, and Manufacturing Engineering at Oregon State University. He serves as the manufacturing engineering undergraduate program coordinator, most recently leading a curriculum redesign in 2018 that resulted in a four-fold increase in enrollment. He is lead PI for an NSF ECR: PEER project developing an online curriculum in mechatronics for manufacturing engineering, and serves as director of OSU's DOE Industrial Assessment Center (IAC), focused on workforce development through experiential engineering education at the undergraduate and graduate student levels. His research focuses on manufacturing process and system modeling methods, life cycle engineering, and engineering education.

Don Neal is currently the Principal Investigator/Project Director for the C2 Pipeline program sponsored by the College of Nursing at Wayne State University. His expertise is in program development, implementation and management, which also includes community collaborations, marketing and strategic planning. His entire career has been focused on working with youth in some capacity and his past work experience includes 23 years of management with non-profits and in K-12 education, and ten years in higher education. He has been a project director for 21st CCLC programs for a total of 22 years.

Gül E. Okudan Kremer is the oldest child of high school teachers and has been the only woman engineer in her extended family since her graduation to present. Her education related scholarly works focus on engineering design learning, team dynamics and design performance, and gender differences. Most recently, along with an interdisciplinary team of scholars, she has been studying neurophysiology of creative behaviour and gender differences. She is Dean and Professor with School of Engineering at University of Dayton.