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Lines of Infrastructuring: Revealing and Tracing Educators' Infrastructuring Practices Across Design Implementations

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Abstract: Facilitators in informal spaces play an integral role in creating equitable and engaging STEM rich learning environments for youth. However, the complexity of facilitator's practices is often undertheorized. Infrastructuring, or the process of dynamically designing with infrastructures (Karasti, 2014) gives us one lens to start to understand this complexity. Building on Azevedo's lines of practice theory (2011), we aim to show the value in tracing infrastructuring work overtime in order to understand how facilitators' preferences and constraints are shaping their practice. In this paper we present two traces, called lines of infrastructuring, that make visible the dynamic infrastructuring work of facilitators as they engage in a research practice partnership developing and implementing computing activities in their spaces. We argue that this analysis provides a new lens for understanding the practices of facilitators, and the realities of embedded infrastructures that can restrain the potential for equitable transformation in this work.

Introduction

While many researchers have recognized the opportunities in out-of-school spaces to engage historically excluded youth in rich STEM learning opportunities, much of this research has focused on understanding the process of youth development or the role of new technologies (Barton et al., 2017; Barton and Tan, 2018). In reality, informal STEM ecosystems are supported by many complex factors, or infrastructures, that are not just underappreciated in research, but are often invisible to people in decision making roles (Coburn and Penuel, 2016; Pinkard, 2019). In our efforts to build transformative informal STEM learning environments, we must consider how innovative educational practices and tools are adaptable, sustainable, and equitable. Creating conditions for long term sustainability involves a high degree of coordination across tools, environment, support structures and pedagogical values. Studying infrastructure allows us to attend to the invisibilized and relational work at play within local systems, practices, and environments (Star, 1999), which has implications for how we can effectively design educational practices and tools that meet this high bar of coordination across conditions of support.

In this paper, we focus on the essential work of informal educators, or facilitators, who support and maintain these out-of-school spaces. We aim to make visible their complex practices to navigate or renegotiate these infrastructures, exemplifying high degrees of expertise to make the conditions of implementation sustainability and equitably possible. These practices of facilitators in their learning environments are undertheorized (Hayden et al., 2023; Hladik et al., 2022; Shea et al., 2023). Within the context of a research practice partnership with informal educators we asked the following question: How do facilitators design work with and around infrastructure evolve over time? From our analysis, we present "lines of infrastructuring," a new framework to examine how this infrastructuring work is supported and constrained across types of infrastructure, and this work's relationship to issues of agency and power.

Background

Infrastructure in the learning sciences

Star and Ruhleder proposed the notion of infrastructure as a way to examine moments in which local practices and solutions intertwine with larger-scale structures and technologies. They argue that infrastructure is a "when" not a "what," often becoming visible upon breakdown, and is inherently relational due to its ties to people, practices, and things (1996). This relational nature is important because it highlights the complexity of infrastructure work, that it is often invisible until small gaps become magnified and cause large scale disruption or breakdowns. Building on these ideas, "infrastructuring" has emerged within design-based research as a lens to move away from static views of infrastructure and instead acknowledge the process of dynamically renegotiating, or designing with and around, infrastructures (Karasti & Syrjänen, 2004). An attention to infrastructure as malleable allows us to make visible people, practices, and places where pre-existing infrastructure reinscribes the very systems of oppression that an educational innovation aims to disrupt. It also draws our attention to spaces or

opportunities where there is wiggle room, or the potential for expansion within current structures, and necessitates a deep understanding of where this opportunity for transformation towards more equitable learning environments exists.

Other learning scientists have proposed frameworks to further this understanding of infrastructure within formal learning environments by thinking about infrastructures as existing across distinct categories or dimensions. Building on the concept of infrastructure as relational, Bielaczyc's (2013) social infrastructure framework offers designers a way to pay closer attention to the social resources in formal learning environments to successfully design and implement technology-based tools. This framework includes four dimensions: cultural beliefs, practices, socio-techno-spatial relations, and interaction with the outside world. These dimensions further emphasize that infrastructure is not just physical or material, but also includes social practices, beliefs and relations which are critical to our work.

Within design-based research, Penuel (2019) uses the term "infrastructuring" to talk about efforts that are focused on creating the conditions of support for educators around educational innovations. This includes the study of how, where and when resources are taken up and allows designers to understand how innovations can be implemented equitably across an educational system and be sustainable long term. Jurow et al. (2019) continue to expand on this relationship between infrastructure and equity in their work, showing the complex relationship between infrastructure and injustice, and the ways in which infrastructure can point to the networks of relationships that allow access to certain resources as well as maintenance of the social order. They point to a necessity to "re-mediating" these conditions, or redesigning infrastructure, that can work to shift what is considered consequential in a learning environment.

Infrastructure in informal learning environments

Our work continues to build on these theoretical conceptions of infrastructuring in design work and brings them into informal making and tinkering environments. These spaces are uniquely positioned to build off youth's interests and create supportive environments that help learners develop their identities as people who are capable pursuing STEM careers (Bell et al., 2012; Bevan and Michalchik, 2013; Ito et al., 2009). Although there are meaningful affordances of these spaces due to their positioning outside of traditional schooling requirements and high-stakes evaluation for learners (Rogoff et al., 2016), it is important to recognize that these spaces have their own structures, policies, and practices that can either support or constrain their equity-oriented goals. These conditions can bring about deeply contextualized tensions, contradictions and gaps in infrastructure that can serve to perpetuate inequity and are consequential to the implementation and sustainability of learning innovations (Hladik et al., 2022).

The role of facilitators in informal learning environments

Also crucial to the potential of informal learning environments in supporting equitable learning experiences are facilitators. Within making and tinkering environments inclusive practices must be embedded in the approach, facilitation, and design of programs (Lee and Worsley, 2019). Facilitators play a key role in onboarding participants into these spaces, ensuring that learners can start participating holistically in these environments (Barton et al., 2017; Blikstein and Worsley, 2016). Beyond this, facilitators continue to be integral in the moment to moment learning experiences of participants, as equity is enacted in these subtle but powerful pedagogical decisions (Vossoughi et al., 2020). They are also multiply situated in relation to power, holding significant power in shaping the experiences of participants in their spaces, while their positions are often deprofessionalized and undervalued. Understanding how facilitators take up and evolve their practice is a key aspect of learning how to support facilitators in continuing to grow in their understanding of what equitable facilitation looks like (Roque and Jain, 2018).

Facilitators can also offer a unique perspective on infrastructures in their institutions beyond that of outside researchers or managers, as their professional practice requires daily interactions with these infrastructures. For example, Hladik et al. (2022), elevate the design work of facilitators in informal spaces by showing how viewing facilitators decisions on a museum floor as infrastructuring work allows researchers to better understand the complexity of their decision-making process and how this work makes it possible for participants to have a meaningful experience. Expanding on the relationship between educator design decisions and infrastructure, our previous work has proposed a framework of types of infrastructure that might be analyzed and reimagined within these environments informed by the perspective of facilitators within their spaces (Hayden et al., 2023). Our initial analysis revealed six types of infrastructure that support design and implementation of computational activities in informal STEM environments: institutional routines and resources, social and facilitation practices, institutional and facilitator values, facilitator expertise, tools and materials and physical

space. Based on further analysis of site observations and design memos we conducted for this paper (see Methods section), we have expanded the framework to include a seventh dimension, community expertise.

1. *Institutional routines and resources*: Institutional practices or rules that impact activities and how facilitators engage; resources that can be accessed by the wider institution
2. *Social and facilitation practices*: Learner and facilitator interactions that support engagement
3. *Institutional and facilitator values*: Values that align with ideas of computational
4. *Facilitator expertise*: Knowledge and attitudes of facilitators that impact activity design and implementation
5. *Tools and materials*: Procurement and use of computational materials; specific material properties that support engagement
6. *Physical space*: Arrangement of resources within the physical environment
7. *Community knowledge*: Designing and implementing activities to connect broader/local community's priorities and expertise

Continuing to push forward the learning sciences understanding of the relationship between facilitators, design work, and infrastructure, this paper aims to show the importance of the dynamic, distinctive, and recurrent patterns of infrastructuring that emerge across time. By taking a longitudinal view on the infrastructuring decisions of facilitators, we can better understand the opportunities and constraints that facilitators are navigating as they make decisions, and how those often undervalued or invisibilized decisions, and their visions of what equitable learning looks like, coalesces to make implementation and sustainability of an educational innovation possible.

Theoretical framework

Bringing infrastructure into conversation with theories of "lines" and "traces"

In this work we aim to bring theories in the learning sciences around tracing practices over time, into how we look at infrastructuring work in design implementations. Azevedo's (2011) seminal concept of "lines of practice" shows us the importance of recognizing patterns and clusters of actions and their relationship with preferences and conditions of practices, giving us a new way to understand the dynamic nature of interest development. In his work, "preferences" refers to the "variety of long-term goals, values and beliefs" that shape a learner's interest trajectory and "conditions of practice" points out the existing constraints and affordances that shape practice. An attention to the preferences and conditions of facilitators in informal learning environments, and how they bump up against or enmesh with infrastructure can also show us where educators have agency to design or "re-mediate" (Jurow) preexisting infrastructure to fit their vision of equitable learning, and where infrastructures feel intractable and must be worked around.

In Vossoughi et.al's (2020) work on embodied pathways and ethical trails, we also see the importance of relational histories within facilitation decisions, and how even decisions on a micro scale, such where educators place their hands when working with learners, can be imbued with particular pedagogical values and can mediate future action and meaning for learners. In this work we show that design decisions, particularly infrastructuring decisions, are also laden with their own relational histories and are in tune with visions of possible futures for learners.

To classify and describe the infrastructuring work of facilitators over time, while taking into account complex and overlapping material and sociocultural factors in their learning environments, we propose the theory of "lines of infrastructuring." Applying this framework to facilitators' iterative learning design practices allows us to make visible the patterns of decision making in this work and categorize how the myriad of external infrastructural factors and facilitators' own values are impacting the implementation and engagement of novel computing activities in their spaces.

Method

Context

This paper reports on data collected from a research-practice partnership (RPP) between multiple US-based universities and informal STEM education organizations. The partnership centers around the collaborative design, implementation, and evaluation of "computational tinkering" activities, an approach that aims to broaden the styles of engaging with computing that prioritizes relationships, joy, and creative explorations of physical and digital materials to create personally meaningful artifacts. The university partners were located in the Mountain West and the Northeast areas of the US. The three informal learning organizations included six makerspaces in a

public library system in an urban Mountain West area, a making and tinkering space within a science museum in the Western US, and an international network of community technology centers. The authors of this paper are part of the university partner in the Mountain West area. As part of this collaboration, partner organizations participated in "R&D threads," which included collaborative iterations of computational tinkering activities, materials, and tools.

Data collection

Data sources include observational field notes taken at partner sites, ethnographic interviews with facilitators located at the partner sites about their design work and documentation collected from iterative and collaborative computational tinkering design work including meeting notes, photos, and video documentation of virtual and in-person workshops, artifacts, and design memos spanning from Fall 2020 to Spring 2023. In total we worked with 16 facilitators, six from the library makerspaces, five from the museum making and tinkering space, and five from the community tech center. Participants had a variety of backgrounds and roles in the organization and none of the participants had formal educational or professional backgrounds in computing. All participants were paid staff members. This repeated engagement allowed our team to learn about the evolving dynamics of these spaces over time and build relationships with staff and participants as we engaged in design work across multiple R&D threads together.

Analysis

This analysis builds from our previous work to develop a framework of the types of infrastructure that support the design and implementation of computational tinkering activities in informal STEM environments (Hayden et al., 2023). Using the data set described above, we created analytic memos that detailed the participation of each of the facilitator's involvement in design work around computational tinkering across our RPP. We then coded these memos to indicate which of the six types of infrastructure were being negotiated in their design decisions, tracing the emergent infrastructuring work of each educator as they imagined, implemented, reflected, and iterated on an activity design, curated materials, adapted their facilitation practices, and arranged the physical environment. Through this analysis, an additional type of infrastructure "community knowledge" emerged that we added to the framework. In coding these analytical memos using the seven infrastructural categories, patterns around preferences began to emerge around facilitators' design decisions. To define a line of infrastructuring, we identified a series of infrastructuring decisions that reflected continuous negotiation along the intersection of a facilitator's preference and their infrastructural conditions. This focus on recognizing and tracing patterns over time to make the breadth and depth of each line visible is based on the analysis process of "lines of practice" from Azevedo (2011). In the next section, we present two such lines of infrastructuring that vary in their complexity. The first case study "material conscientiousness" shows how a consistent preference along a particular infrastructural dimension shapes one facilitator's practices across two R&D threads. The second case "building connections" shows a more complex preference that cuts across infrastructural dimensions, generating new breakdowns and bumping up against conditions of practice that necessitate continuous negotiation over time.

Findings

Case 1: Material conscientiousness

In this case we show how one facilitator's preference around the intersection of her *value* of sustainability around *tools and materials* fundamentally shaped how she engaged in the design process with our team across two distinct R&D threads. At the start of this line, we presented Katie with some sample activities to try out at her space and she expressed interest in an activity called Scribbling Machines and its possibilities to connect with her community's interests in art and pattern making. The Scribbling Machines activity includes a motorized contraption and moves in unusual ways, leaving a mark to trace its path. As we began an R&D thread together in Katie's makerspace, Katie's preference around being waste-conscious began to bump up against the current design of the activity, which used a lot of packing tape and single use plastic cups. In conversations with our team Kate mentioned that sustainability and upcycling are also appreciated by the wider community that attends the space, and that they would be uncomfortable with an activity that they perceived as wasteful. This revealed a breakdown in values between the current design of the activity and the values of Katie and her community.

As a co-design team, our research team and Katie brainstormed around alternative connectors to avoid wasting large amounts of tape, deciding to opt for materials like Velcro loops and rubber bands. In preparation for the workshop Katie also leveraged her network at the library branch to put out a call to library staff to collect recycled food containers for the scribbling machine bodies instead of the single use plastic cups. These decisions

to use recycled food containers and reusable connections meant that more time needed to be spent by our combined design team to prepare the containers by cleaning them and poking holes, but that the activity would produce less waste.

A few months later Katie collaborated with our team again around a new R&D thread to design an activity around lantern-making using computational tools. During this process a new facet of the "material conscientiousness" line takes priority as Katie is emphasizing the use of "everyday" materials and processes. We found that this preference first emerged in her interview with us at the beginning of the project where she shared that she and her co-facilitator created take-home activity cards during the Covid-19 pandemic that focused on low-cost, recycled, and everyday materials that people have at home. In the R&D thread, this value manifested as using wax paper and irons to create the lantern forms, materials, and tools that participants would be familiar with and have access to at home. A focus on low-cost materials also related to her economic concerns with materials as she both has to pay attention to her own budgetary constraints as well as for participants who might try this activity at home.

Case analysis

In this case, Katie is responding to and designing with her ecology of infrastructures in order to support implementation and engagement of these two activities in her space. Without a longitudinal view on Katie's design decisions, it is easy to miss the ways that her everyday infrastructuring practices make engaging in a computational tinkering workshop for her participants possible and meaningful. Although the decisions shown here are mainly shaped by a preference along the dimension of *tools and materials*, her decisions also interface with other dimensions of infrastructure. She leverages her *institutional resources* to collect the recycled materials, both her *facilitator expertise* and available *tools and materials* to create alternative ways of engaging in activity that are more sustainable and/or economical for her space and displays her *expertise* around the *values of her community* to know that these decisions would be important for them to feel recognized and motivated to engage in these activities.

Case 2: Building connections

In other cases, lines of infrastructuring reflected preferences and conditions of practice that were more complex, requiring repeated design work that deeply cut across multiple infrastructural dimensions. At times, the design work was easily incorporated, and at other times, the design work created additional breakdowns to re-mediate. In this case, we trace a line called "Building Connections" that shows how one facilitator Luis aimed to ensure that his participation in our RPP could be incorporated back into the day-to-day experiences of the youth and families in his makerspace, and tangibly benefitted these participants as much as possible. Here, we focus on his work in collaboratively designing and implementing a workshop together called "Family Light Boxes."

Prior to the current RPP, Luis has worked with our team since 2018. He joined the library makerspace network in 2017. Together, we implemented workshops for families to create and learn with computational technologies such as ScratchJr, paper circuits, LEGO WeDo, and Scratch. In these early collaborations, we adapted pre-existing programs and activities developed by our team into the makerspace. In the current RPP, our team expressed our intention to engage more collaboratively in the creation of new activities for youth and families through R&D threads, hoping to develop computational tinkering activities that emerged organically from the interests of Luis and his community, rather than adapting pre-existing activities.

This line began with Luis sharing about a community storytelling project happening at the library, and that he thought we could build on this theme in our work together. In addition to existing materials in the makerspace, he also expressed an interest in incorporating physical computing kits like the Circuit Playground Express into the workshops, a tool that he had purchased previously for another program but remained unused in a closet. He hoped to demonstrate the exciting potential of these kits as materials they can use in the makerspace by leveraging this theme of community storytelling to engage participants in meaningful and personally relevant ways.

Unlike our past collaborations, where much of our explorations of materials, technology and iteration on activity prompts would happen through virtual meetings or asynchronously with our team curating materials at our university, Luis asked that we instead conduct the R&D in person at his location during Open Lab hours, when participants would be present and engaging in their own projects. This request reflected his preference that our work tangibly engage with his participants as concretely as possible. He expressed that by conducting our R&D together at his space during Open Lab, participants would be able to see computing tools in use in new ways, grow more familiar with our team and engage with us as we worked, and it could act as advertisement for the upcoming workshop series. This preference was also shaped by Luis's conditions of practice. In his role, he had limited time available to him outside of Open Lab hours, which he often spent on maintaining/repairing the

machines in the lab, preparing the lab and its materials for the public, and participating in meetings within his library branch or with the library makerspace network. As such he had very limited time to explore new materials and activities that could be used in the makerspace, and thus limited available time to do any R&D related to our workshop planning. While our RPP had funds to compensate Luis to participate in R&D, it was against city policy for public library staff to accept additional compensation.

This shift in our working modality afforded multiple opportunities. In line with Luis's value of making sure that our work was grounded in the interests and reality of his participants, by working in the makerspace during Open Lab, Luis invited the R&D process into the relational environment that he had been cultivating throughout his years with the community, and ensured that the materials, tools, and process of our work together were made visible to those who were in the space. Young people who started to recognize our team over time would ask us what we were working on and could be invited to try out tools and to share their opinions as we planned an upcoming workshop series. The Teen Mentors, part-time paid high school facilitators, also became invested in our R&D, and chose to use their available time in the lab to help us create 3D printed supporting materials. They also learned to solder in order to help us wire LED lights.

However, Luis's infrastructuring work also faced new breakdowns as a result of this shift. Because the makerspace had about 3-4 open project tables, sometimes our team would arrive, but there would be no available tables or chairs. Luis had to grab yoga mats from a different part of the library so that we could work on the floor. An additional breakdown came from his available time during Open Lab. When there were lulls in participation, Luis got updates and worked with the materials with our team. However, Luis's main priority during Open Lab was always welcoming, supporting, and connecting with participants who were working in the space. At any time, Luis was working with a range of participants from young children to older adults who sought help on a wide array of projects from 3D printing to producing beats in a music studio. While Luis's decision to shift our design work into Open Lab opened up the design process to the public, Luis still ran into infrastructural constraints on his time and capacity to participate fully.

In the end, the makerspace participants' familiarity with our team and the activity allowed Luis to recruit families that may not have typically joined a computing workshop. During the series, Luis continuously worked to connect the "Family Light Box" projects that participants were creating to their participation in the makerspace during Open Lab Hours. He shared examples of how they could continue to complexify their projects after the conclusion of the workshop series or create alternative projects using the skills they had learned in the workshops.

Case analysis

By inviting us to R&D during Open Lab time, Luis leveraged an *institutional routine/practice* that opened up the makerspace to the general public, enabling him to be more involved in the process, while not sacrificing the few hours he had when the lab was closed to catch up on administrative tasks. However, Open Lab time was also a constraint, as Luis's primary priorities were to support participants in their varied projects when necessary, requiring additional infrastructuring work when there was not available *physical space* for our team. Luis leveraged the *tools and materials* in the space by encouraging us to design around his set of Circuit Playground Express kits, and by using other tools in the space such as the 3D printer and soldering equipment. *Facilitator values* and *expertise* were key to this R&D work, as the Teen Mentors became important contributors to our design work, and our collective social and *facilitation practices* spurred by Luis allowed *community knowledge* to be leveraged as participants of the makerspace were brought into our process and provided input.

We called this case "building connections" because Luis's infrastructuring work across dimensions can be traced back to this preference. He first set out to connect our R&D thread to the interests of his community, storytelling, and his available computing tools. In moving our R&D into his space, he is intentionally building connections between our work and his participants—allowing us to better understand community values and interests, build relationships, and invite community members to engage more directly in the R&D work. In this case, Luis is navigating and designing with his ecology of infrastructures in order to shift the center of our design work from an inaccessible space like a university into a public space, where we could privilege community knowledge and relationships. However, Luis's infrastructuring work was not without resistance or friction as some infrastructures were either hard or impossible to redesign such as the physical dimensions of his space or even how his roles and responsibilities were defined for his position.

Discussion and conclusion

We see this framework as contributing to growing scholarship of infrastructuring work within educational partnerships. Lines of infrastructuring gives researchers a new way to make visible the dynamic nature of infrastructuring work as it unfolds across time, expanding our ability to parse what supports and constrains educators to implement innovations sustainably and equitably in context. In the case of Katie, we see how her

preferences are shaped by her values around accessibility and sustainability of tools and materials, driving how she engages in infrastructuring work to successfully incorporate computational tinkering activities in her space. In Luis' case, we see how his preference for building concrete connections between the people, products, and practices of our RPP and his community required iterative infrastructuring work—work that created new opportunities, but also faced breakdowns as he ran into infrastructural challenges and resistances.

For the learning sciences, this analysis gives us a new way to make visible the labor required by practitioners as they incorporate new tools, activities, or collaborative processes and partnerships—even when the aims of the partners involved are closely aligned. When we began this partnership between multiple US-based universities and informal STEM education organizations, we were intentional to frame the work of practitioners (or facilitators) as research. The concept of an R&D thread comes from our museum partner, as they purposely and explicitly frame the design work of educators as research to communicate with their colleagues and collaborators the nature of this work. However, while this is one step in elevating the expertise of educators, this naming is still fraught. For example, for Katie and Luis, "research" is not part of their job description as library staff. Although it is clear that both educators are doing integral infrastructuring work to make both our partnership possible and the resulting learning innovations meaningful to their participants, this work is rarely acknowledged by their colleagues and decision makers within and beyond their organization.

One of the properties of infrastructure from Star is embeddedness, or the way in which infrastructure is "sunk into other structures, social arrangements, and technologies" (1999). Through tracing these lines of infrastructuring, we can see how facilitators in these cases themselves are acting as infrastructure, deeply embedded into the fabric of their spaces and key to the success of implementation and engagement with learning innovations. However, throughout our work together, we have seen how this embeddedness can also serve to invisibilize the expertise that guides their work. Facilitators in these roles have little to no upward mobility, and when faced with staffing shortages, their positions remain precarious despite years of experience. In the case of Katie, she was moved to another role within the library system soon after our lantern workshop, which halted our R&D work together. Luis has since left his position, telling our team that the persistent lack of recognition from his supervisors and low compensation for his work made staying untenable. This fact is also echoed in Shea et al., (2023) pointing to a harsh reality that despite the integral nature of facilitators in advancing equity-oriented work in these spaces, the sustainability of this work is undermined by systemic infrastructural injustices. This framework can provide researchers with a tool to make facilitators complex practice visible, allowing our field to advocate for the crucial role of these educators more effectively and elevating how they might be better supported.

In taking a close look at the process of negotiation and iteration surrounding the intersection of facilitator's preferences and conditions of practice, lines of infrastructuring emphasizes that learning environments are made up of and exist within complex systems of power. In Katie and Luis's cases, we can see two educators who are empowered to re-mediate infrastructures around them, creating possibilities for engagement in computational tinkering activities in their spaces. In recognizing "lines of infrastructuring", or patterns of where facilitators find opportunities and face constraints in their design work, we are able to see where there is wiggle room in these systems to disrupt infrastructural injustices. However, it is important not to reinforce the myth of the "hero" educator, that an individual can be expected to champion learning innovations alone or be blamed for their failure. Rather we aim to show that despite Katie and Luis' investment, expertise, and resourcefulness, the transformation required to bring about educational justice requires disruption of multiple levels, beyond what an individual educator has power over. As the field of the learning sciences continues to work towards new methods of educational justice, we argue that researchers need to also recognize and examine these patterns of resistance and opportunity that can support or constrain the transformative work of informal educators.

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