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Community laboratories in the United States: BioMakerspaces for life science learning

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Abstract
Informal learning environments play a critical role in science, technology, engineering, and mathematics learning across the lifespan and are consequential in informing public understanding and engagement. This can be difficult to accomplish in life science where expertise thresholds and logistics involved with handling biological materials can restrict access. Community laboratories are informal learning environments that provide access to the resources necessary to carry out pursuits using enabling biotechnologies. We investigate a group of these spaces in order to ascertain how this occurs—with specific attention to how material and intellectual resources are structured and shape learning. Using surveys and focus group interviews, we explore a group of these spaces located in the United States. We found that the spaces examined offer learning activities that are sufficiently scaffolded and flexible as to promote personalized and community-driven practice. We discuss these findings in relation to informal learning environment design and learning.

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1. Introduction

In the United States and internationally, community laboratories are becoming a more populous space for informal life science learning (Jorgensen and Grushkin, 2011; Talbot, 2020). They provide public access to the tools and expertise necessary to conduct diverse life science learning activities not typically available in libraries, museums, or other informal learning spaces due to the need for specialized equipment (King et al., 2018), extended and collaborative participation in co-creation activities (Cigarini et al., 2021), and time-intensive partnerships between science specialists and educators (National Research Council, 2009). Example learning activities include the use of biotechnologies to produce biologically based art, biosensors, food products, and construction materials (Kafai and Walker, 2020; Kuldell et al., 2015; Walker, 2021; Walker and Kafai, 2021).

Despite these inroads for community laboratories, the current literature does not address or conceptualize the learning environment design or processes that occur in these spaces. This is in part because community laboratories are nascent and use life science resources that have only recently been leveraged in learning. The result is a dearth of frameworks with which to investigate or understand these sites in terms of how and whether they support learning, broaden participation, and/or support critical civic and participatory practices that are key outcomes in science, technology, engineering, and mathematics (STEM) education and public engagement (Hecker et al., 2018; National Academies of Sciences, Engineering, and Medicine, 2018).

We attend to this gap by providing the first systematic investigation of learning in community laboratories, paying close attention to their design and educational utility. We use two frames to guide our investigation—constructionist perspectives on informal learning environment design and constructivist perspectives in active learning in science. We examine how community laboratory resources and expertise are structured as learning environments and how those arrangements shape learning and outcomes. The resulting insights situate community laboratories within the diversifying milieu of informal learning environments and shed light on how their activities extend our conceptualizations of informal learning in contemporary life science.

Perspectives for understanding science learning in informal environments

Informal learning environments support learning beyond formal school settings and include out-of-school-time programs and spaces such as summer camps, museums, libraries, and home environments (National Research Council, 2009). Informal learning environments are important in part because they make accessible content areas not traditionally included in formal STEM education (Van Holm, 2014). They also broaden access to groups that don't usually occupy formal learning spaces, such as individuals who wish to engage beyond traditional areas of study (Maiorca et al., 2021). These benefits also reach individuals across life stages.

Informal learning has been impacted not only by the growing diversity of spaces in which it occurs, but also by movements in open science and open participation, which are spurred by principles of transparency, broad dissemination, and active engagement between the general public and scientific professionals (National Academies of Sciences, Engineering, and Medicine, 2018). Open science practices encompass a broad range of activities: citizen science, in which the research questions are often defined by professional scientists with members of the public engaging in data collection and analysis (Hecker et al., 2018), community-based participatory research, in which professionals and the public engage collaboratively to define research questions based upon the priorities and values of both communities (Wallerstein et al., 2017), and the Do-it-Yourself (DIY), FabLab, or Maker approaches, in which project ideation is driven entirely by individuals who are encouraged to enter the space as novices and draw on the tools and expertise provided by the community (Maravilhas and Martins, 2017).

Makerspaces, framed as open science and DIY movements, are relatively nascent in STEM learning, but have nonetheless matured into spaces that complement science education efforts across expertise and age groups (Halverson and Sheridan, 2014; Peppler et al., 2016b). As informal learning environments, Makerspaces can encourage a community of knowledge sharing, collaboration (Anderson, 2012), and artifact creation—often through the use of cutting-edge technology. Examples include the construction of useful digital artifacts like interactive robots, games, and wearable technologies (Peppler et al., 2016a). There is also evidence that learning arrangements in these spaces are significant in sustaining engagement across critical demographics (Peppler and McKay, 2013; Tan and Calabrese Barton, 2018; Vossoughi et al., 2016).

We thus draw on a constructionist learning design metaphor, first proposed by Seymour Papert (1993) and then applied to makerspaces by Peppler and McKay (2013). In this metaphor, important learning design features are those that enable novices to participate immediately ("low floors") and, over time, carry out sophisticated processes ("high ceilings"). Resnick and Silverman (2005) broadened this idea to include "wide walls" or features that enable diverse forms of engagement, for example, learning experiences that enable non-experts to build simple programmable circuits and, eventually, computationally sophisticated artifacts over personally meaningful learning trajectories. Community laboratories share several important characteristics with makerspaces, including the focus on artifact creation and a culture of knowledge sharing and collaboration (Jorgensen & Grushkin, 2011; Talbot, 2020). We use Peppler and McKay's framing of makerspaces as an important starting point for examining community laboratory organizational designs and participant engagement. We recognize that there are important distinctions between makerspaces and community laboratories—such as the latter's emphasis on the life sciences. We therefore aim to assess how community laboratories fit within or extend constructionist ideas about informal learning environment designs in relation to learning and public engagement.

Constructivist perspectives on active science learning and practice

To understand both the traditional and more contemporary forms of learning practice that might occur in community laboratories, we also use constructivist ideas in active learning, a stance that moves beyond didactic instruction and into experiences where learners themselves actively construct and enact knowledge through authentic and situated acts (Anderson et al., 1996; Brown et al., 1989). This is an iterative process wherein learners themselves make observations, reflect, and reconcile ideas (Olsen, 1999). There is growing evidence that active learning in STEM enhances innovation, occupational pipelines, and public literacy (Freeman et al., 2014; Graham et al., 2013). However, far less work has been done to examine active learning in environments that engage modern life science and biotechnologies (in their emphasis on material production), where participation is paradigmatically different from traditional life science emphases on inquiry or induction. Our research offers an opportunity to understand whether and how community laboratories support educational growth through active learning.

We use several lenses for this examination. First, we leverage science and engineering practices drawn from the Next Generation Science Standards because it is a widespread US science framework developed to promote active learning through a process of investigating and modeling science phenomena—typically through inquiry and experimentation (NGSS Lead States, 2013). Second we adopt design principles, by which we mean a culturally situated "analytic and creative process that engage[s] a person in opportunities to experiment, create and prototype models, gather feedback, and redesign" (Razzouk and Shute, 2012: 330). This conceptualization also has an explicit emphasis on creativity, convergence, feedback, and critique; in other words, alignment of scientific outputs or production with social and cultural values. Finally, we draw on maker practices to account for production that emphasizes DIY engagement with materials to design and produce artifacts with personal and functional utility. Maker practices (Sheridan et al., 2014; Vossoughi and Bevan, 2014) are conceptually significant in this study because they emphasize creativity and material production in ways that have only recently become possible in life science due to the development of enabling biotechnologies.

These perspectives on informal learning environments and active learning enable us to answer two fundamental questions about community laboratories: (1) What is the nature of materials, practices, and participation in community laboratory spaces? and (2) How do community laboratory resources and organizational structures inform what we know about learning in informal environments?

2. Method

Community laboratories and participants

Study participants included 73 community laboratory members, who responded to a survey distributed to nine US community laboratories. Laboratories were purposefully selected because of regional distribution, overall size, and for a diversity of mission objectives (e.g. education, community engagement, scientific research) as listed on each organization's website. Participants' self-identification with demographic categories is summarized in Supplemental Table 1. Seven participants from four community laboratories were purposefully selected for focus group interviews based on their diversity in age, professional background, community laboratory experience, and survey responses.

Data collection instruments

The survey instrument used in this study asked participants about their engagement in three categories of learning practices (both the survey and Table 1 are grouped by these practices). These categories are derived from science and engineering practices identified in NGSS Lead States (2013) framework, design practices described by Razzouk and Shute (2012), and maker practices reported by Sheridan et al. (2014). The survey underwent two rounds of revision after collective feedback from two semi-structured focus groups composed of 30 high-school-aged youth and three adult science educators. The final instrument consisted of items arranged by practice category and asked the frequency with which a participant engaged in each practice. To provide more nuanced and triangulated qualitative insights to survey items, three follow-up 90 minute focus group interviews were conducted to gather information about community laboratory resources and participant learning experiences. Focus groups were selected to create space for consensus-building among participants who were each purposefully selected to contribute input to our emerging theory (Morse, 2016). Participants were asked questions about how they came to learn about their community laboratory, why they came to join the laboratory, what resources are available in these spaces, and the type of activities in which they participate.

Table 1. The percentage of community laboratory participants who report carrying out science and engineering, design, or maker practices.

Practice category	Specific practice	%
Science and engineering	Explore living materials (e.g. organisms, cells, plants, etc.)	75.3
	Analyze and interpret data	75.3
	Learn and apply new ideas	72.6
	Get feedback about ideas or projects	61.6
	Collect, exchange, or share resources (e.g. laboratory reagents, devices, sharing laboratory space or software licenses)	60.3
	Share my ideas or projects with others	60.3
	Change an idea or way of thinking	56.2
	Make changes to a project I carried out	45.2
Design	Ask questions and identify problems	69.9
	Research an idea or concept	64.4
	Collaborate with others to solve a problem	64.4
	Plan and carry out an experiment	58.9
	Design a project	52.1
	Solve a problem when carrying out a project	52.1
	Design something for people other than myself	39.7
	Make or use a model	34.2
Maker	Make explanations for problems (i.e. develop and understand a problem)	45.2
	Explore materials to make objects or art	37.0
	Make something that is personally meaningful to me	32.9
	Make an argument based on facts	31.5
	Create new products	28.8
	Make a project that expresses who I am or that represents something about me	13.7

Data collection and processing

The survey was administered using Qualtrics, a computer-based tool, over a period of 2.5 weeks. Survey responses were coded (i.e. converted from text to numerical values) using a Microsoft Excel spreadsheet. Focus group were administered by the authors using Zoom, an online video conference tool. Interviews were transcribed using Otter.ai, an Internet-based transcription service, and then imported into Google Docs and excerpted by question for analysis.

Analysis

Survey data were analyzed using the SPSS statistical package to generate descriptive statistics. Where appropriate, a Levene statistic confirmed survey data met parametric testing distribution and homoscedasticity assumptions. Focus group interview transcripts were coded and assessed using deductive and inductive approaches (Ravitch and Carl, 2019). Codes were applied independently by authors 1, 2, and 3, and disagreements were resolved until full consensus was reached. We also generated descriptive codes that enabled us to address the following ideas: (1) How did the focus group come to participate with their local community laboratory? (2) With which activities or practices did focus group participants say they engaged?, and (3) What did the focus group participant's responses reveal about learning arrangements in the space? We then developed case

Figure 1. Community laboratory space configurations in the (a) Mid-Atlantic, (b) Northeastern, and (c) West regions of the United States.

study narratives with illustrative themes drawn from interviewee responses. The authors discussed themes and narratives iteratively until interpretative agreement was reached.

3. Findings and analysis

Community laboratory engagement, materials, and practices

The most common reasons survey respondents gave for why they attend and participate in their local community laboratory was to meet or collaborate with others (80.8%) or to learn new topics (82.2%) or skills (68.5%). Fewer (54.5%) indicated they did so to work on a project for personal enjoyment, or reasons other than these (13.7%). This result confirms community laboratories as unique access points for life science learning, in addition to being spaces that facilitate social engagement and personal pursuits.

Survey participants also reported using or planning to use a range of biotechnology tools (Figure 1). The most common type of equipment participants reported using were tools to handle biological materials (e.g. incubators, Petri dishes, microscopes, and personal protective equipment (PPE)) (Chart 1). Digital resources (i.e. tools to analyze data or give presentations) and maker equipment (e.g. sewing machines, laser cutters, pottery wheels, and microcontrollers) were reported to a lesser extent. This is consistent with the idea that community laboratories are uniquely suited for life science engagement. Notably, community laboratories deviate from typical life science laboratories insomuch as they *do* include tools typical of other informal learning environments such as audio-visual and makerspace tools.

Survey participants also reported having opportunities to carry out a range of practices (Figure 2) consistent with active learning in science and engineering, design, and making. These included extensive use of science and engineering practices as shown in Table 1. Design and maker practices were reported, but each to a lesser extent. When considering demographic-based variations, we observed no gender-based differences with regard to science and engineering ($F(2, 70) = 0.134$, $p > .05$), design ($F(2, 70) = 0.173$, $p > .05$), or maker practices ($F(2, 70) = 0.538$, $p > .05$). We also observed no age-based differences with regard to science and engineering ($F(2, 69) = 1.631$, $p > .05$), design ($F(2, 69) = 0.109$, $p > .05$), or maker practices ($F(2, 69) = 2.801$, $p > .05$). This suggests that participation in these community laboratory practices spans across gender and age groups.

Community laboratories as informal learning environments

To further nuance and add context to the descriptive results, we present our focus group data as three illustrative cases grouped by age to emphasize the reach community laboratories—consistent

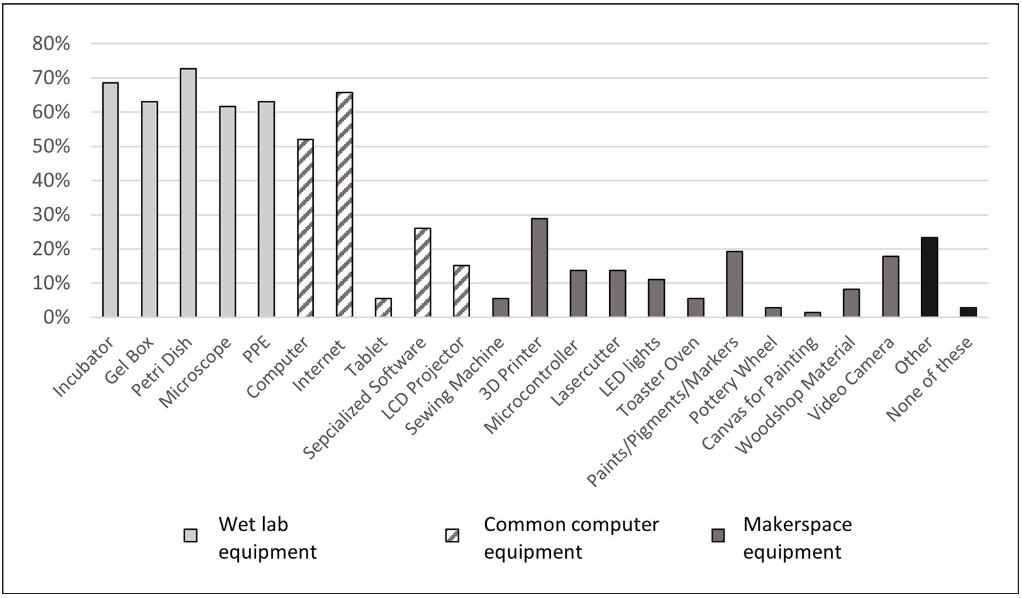

Chart 1. Tools participants report being available for use in their local community laboratory. Responses indicate the percentage of participants who report having access to use wetlab, computer, or makerspace tools.

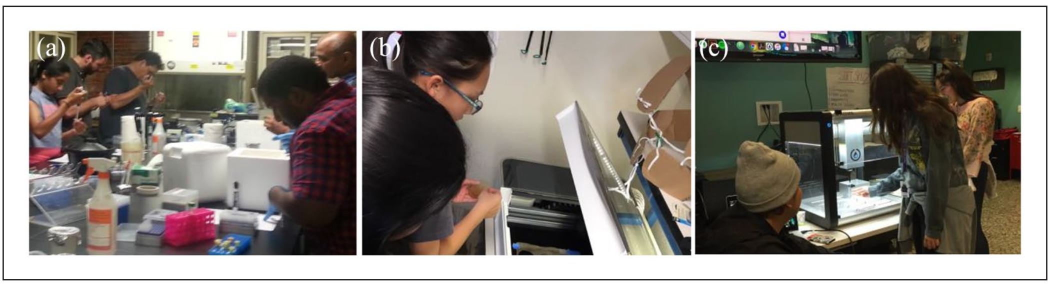

Figure 2. Community laboratory participants in the (a) Mid-Atlantic, (b) Northeast, and (c) West regions of the United States carrying out learning activities.

with informal learning environments—have in supporting informal learning in the life sciences across life spans. To highlight the similarities and differences across cases, we describe what participants had to say about learning in their local community laboratory and our observations about what appear to be transformative learning trajectories.

Our first case included high schoolers Harold and Arunav, who were both members of the BioCommunity Space. Each had distinct forays into the space, which we assessed, respectively, to be through formal school influences and family. Harold learned about the space approximately a year prior through his school guidance counselor who advised about out-of-school-time opportunities in life science that could extend and build on his growing interests. Arunav had been involved with BioCommunitySpace since he was "around ten or eleven" years old when he'd "tag along" with his older brother who was a member (Focus Group Interview, 8/9/2020, 00:05:27). Both youths began participation as novices with little to no formal experience in these environments.

When asked about their learning experiences, both Harold and Arunav described initially participating in what we observed to be collaborative projects that were highly structured—an arrangement that was effectively a scaffold into inquiry-based laboratory research under the direction of more experienced mentors. This support enabled them to shift along a learning progression that appeared from our assessment of their response to be both personalized and suited for their expertise. The participation they reported was also situated in authentic acts of the discipline, as each youth carried out increasingly sophisticated laboratory techniques (from learning about life science tools to handling biological materials) and practices (from following structured protocols to troubleshooting their own experimental designs). This was reflected in an anecdote Harold shared about a project to develop an open-source bioprinter—a device that could seed plant cells onto a nutrient scaffold where they could grow—as he reflected:

> We would mix the agar and cool it in the hood and then we would plant . . . what we want to grow in the petri dishes . . . and we would we would find out if any had like mold growing or if any looked like they couldn't really grow anymore . . . we kind of just take note of this on a spreadsheet and we track like what are some causes as to why they might have died. Originally carrots were the primary plant cell to grow in like these kinds of bioprinters or like, just in general these experiments, but we found that carrots were more prone to, like, mold and disease. (Focus Group Interview, 8/9/2020, 00:39:18)

Harold described the selection of technical tools and experimental practices as well as making sense of related findings, each of which is authentic to laboratory practice and typical of active learning in life science. Furthermore, Harold's matter-of-fact explanation reflected his deep understanding, and is certainly beyond what would be taught in formal settings at his age in the United States. His work represents important growth that signaled he was no longer a novice entering the space for extracurricular activity, but rather a budding and agentic scientist able to navigate and conceptualize in detail his role as a productive laboratory member.

At the time of our focus group, Arunav was in a different stage of learning and engaged mostly with independent experiences and in making contributions to the space? This was reflected in his role in a peer teaching program, wherein he instructed a series of laboratory exercises, a position he acquired after having mastered the course as a student. As he put it, "I've been on both sides" (Focus Group Interview, 8/9/2020, 00:10:51). Arunav's description of this transition suggests he had moved beyond the socially initiated ("tag along") role he described as his beginnings in the space, and into an active contributor role, shepherding others along as he had been. Arunav also shared his involvement with inquiry-driven research, as he reflected, "I also do my own research at BioCommunity Space, like individual research. [I have a project] going on there. And I work with the mentors there on my own scientific research so I'm part of both the community projects, but also my own individual projects as well" (Focus Group Interview, 8/9/2020, 00:11:04). Arunav went on to describe how he designed his own experimental protocols and came up with his own implementation strategies after periodic consultations with his mentors (Focus Group Interview, 8/9/2020, 00:52:56). These anecdotes illustrate not only Arunav's command of scientific ideas, but also his growing practical acumen as a teacher-scientist, imbued with an efficacy to both impart knowledge and pursue lines of inquiry of his own. Our observations suggest each youth had very different experiences, and yet both had opportunities to participate in advanced activities which ultimately transformed their learning and roles as each shifted from consumers of processes and structures instituted by others into active contributors. The cases of Harold and Arunav represent the role that community laboratories serve as informal learning environments for youth engaged with burgeoning areas of life science. We address these insights further in the "Discussion" section.

Our second illustrative case is of Nicholas and Mariah, young adult members of different community laboratories. At the time of our interviews, Nicholas was an industrial designer who as an undergraduate had an interest in bioart (i.e. making art with biological materials). After college, he searched for a place to "find more design inspirations" (Focus Group Interview, 8/10/2020, 00:04:06) and found DNA Bio Space through an Internet search (Focus Group Interview, 8/10/2020, 00:07:14). Nicholas's introduction to the community laboratory was prompted by personal motivation to extend his professional experience and interest. Mariah, a college freshman, learned about City Community Lab through an internship in high school where a mentor encouraged her to join a team of others competing in an international synthetic biology competition, resulting in a 2-year engagement with the laboratory. Like all participants we interviewed, the community laboratory served as an important entry point for Mariah to learn about areas of life science not otherwise available to the general public.

We characterize Nicholas's initial experiences as apprenticeship, where he learned by carrying out supervised technical tasks related to managing the laboratory. This helped him develop familiarity (and mastery) with laboratory reagents and tools. He explained, "I wanted to learn a little bit. So I've helped with inventory, not really knowing what the chemicals would do, but at least putting them on the shelf and helping out with that" (Focus Group Interview, 8/10/2020, 00:12:04). Over time, Nicholas's participation shifted to more masterful practices, and eventually, "expanded off to helping with their open house and helping TA for one of the classes right before COVID. We were doing bioplastics, and I was part of that for a moment" (Focus Group Interview, 8/10/2020, 00:12:14). Working with bioplastics was consistent with his initial ambitions which would eventually broaden as he apprenticed into more technical work and deeper and contributions. Nicholas summarized his learning:

> I was hoping for, at least getting my foot in there and to get like, again, more familiar with the lab, more familiar procedures and adequate I would say, at being in a lab, especially communal one . . . Because I think it's interesting. I'm still though, trying to figure out like a project that myself personally to get started invested in, but I was and still am really interested, interested in helping others with their projects, at least being kind of a handyman and being like, helping out with this or helping with that and just learning. (Focus Group Interview, 8/10/2020, 00:12:14)

Our assessment of Nicholas's experience suggests he is apprenticing into authentic practice through technical exercises that would ordinarily be carried out by a laboratory manager or "handyman." He recognized this framing was meant to develop a skill set that would eventually lead to working independently on a project of his own—a transformative outcome that he seemed to view as a pinnacle to his participation.

Mariah highlighted the more social aspects of her participation when she detailed her collaborations as a teammate in an international synthetic biology competition. She and her team distributed tasks that helped them achieve the shared goal of designing and creating a genetically modified yeast cell that could degrade environmental plastics (Focus Group Interview, 8/10/2020, 00:09:03). Mariah carried out biotechnology-based laboratory activities that enhanced her acumen and that were transferable to other activities. Examples included onboarding new community laboratory members into technical procedures as she "[walked] them through, like, [polymerase chain reactions] and how to run a[n electrophoresis] gel" (Focus Group Interview, 8/10/2020, 00:13:30). As was clear from our observations with youth, and now here for Nicholas and Mariah, growth in community laboratories is marked by a process of *becoming*—a process of transformation from one who comes to learn from opportunities designed by others to someone who actively and productively contributes to the space. The synthetic biology competition also yielded Mariah chances to share discoveries with peers. Mariah also participated in cooperative research projects that focused on the local community by engaging locals about plastic waste. She explained: "We did a lot of outreach with [City] Beyond Plastic, which is this youth-led activism organization in [the city] . . . [We] did surveys of like community members and asked them what their thoughts on synthetic biology were and like the work that we were doing." (Focus Group Interview, 8/10/2020, 00:29:15). Unlike anecdotes in other accounts, Mariah transitioned toward activities more in line with citizen-science practices that involved the use of science to educate and serve the local community. These anecdotes illustrate that what started as a collaboration for a competition shifted over time into opportunities to practice and exercise laboratory and research skills. These reflect transformations toward engagement not only for self, but also for others in the community.

The case of Nicholas and Mariah also highlights the salient role community laboratories play as important access points for not only pursuing areas of personal interest, as observed with Harold and Arunav, but also to support transformative intellectual, practical and professional growth. In both cases, we observed learning arrangements that leverage apprenticeship and cooperation. Our assessments also suggest that community laboratories enabled, at least for Mariah, opportunities to interweave citizen-science work as she conducted socially relevant projects, reflecting a significant evolution from more self-oriented endeavors to more outward facing and perhaps mature social movements.

Our third case includes Althea and Jerome, adult members of the City Community Lab, and Chanah, a member of Comunidad Lab Space. At the time of our interview, Althea had only recently found the community laboratory space while attending a group "meet up" hosted by the laboratory at a local bar. Althea thought that participation would support her aspiration to attend medical school, which motivated her decision to become an active member. This motivation parallels Nicholas's, where personal and professional aspirations motivate engagement. Jerome found the space several years ago while exploring a list of makerspaces online; his interest piqued when he noticed on the laboratory website that he already knew a member through his prior involvement in a degree program. We found this driver consistent with Arunav and Mariah, whose participation was also prompted through social connections. Similarly, Chanah learned about her community laboratory through professional collaborations with makerspaces and related communities. It was through professional work as a local activist and artist that she eventually connected to the laboratory and the resources it could provide for her to engage with biology-based maker activities—an area with which she was developing a growing interest. Like Nicholas and Althea, Chanah's engagement was prompted through professional pursuits and sustained because the community laboratory served to support those endeavors. For example, Althea explained:

> When I first started, I told Liz [the Executive Director] that I was interested in hands on. She hooked me up with a group that was working on a project. Because it's been a while and I was rusty, [I] did a lot of watching. And I just, you know, paid attention to what they was doing and eventually I started to be able to do stuff that they asked me to do and then eventually I was able to do on my own. I was, you know, I didn't need someone watching over my shoulder to assist me. I was able to carry out, you know, the process and know exactly what was going on. (Focus Group Interview, 8/11/2020, 00:33:18)

Beyond motivation, Althea's experience mirrored that of many of the other focus group participants in that she gained access to material and intellectual resources (knowledge sharing). As a result of this access, she shifted (as we saw in other cases) from being a peripheral participant to being a more knowledgeable member able to contribute productively to the laboratory.

Jerome's initiation into the space was grounded in prior wetlab experience, which was more developed than other focus group participants. Over time, his participation encompassed a range of roles that situated him as a knowledgeable support to others. As his contributions expanded, so did the roles he eventually took on, which included designing research projects for others and leading workshops. As he explained, "[for the lead remediation project] the experimental design was mostly mine, and I actually did a presentation on that" (Focus Group Interview, 8/11/2020, 00:39:43). This shift reflects professional development that started in a more experienced zone and grew into a one that was increasingly sophisticated and contributory. Jerome highlighted what he viewed to be a notable distinction between community laboratories and other informal learning spaces, and the factors that shape how resources themselves function in these environments:

> Anything that gets done there is because of members interested . . . the members are what the space does. And that's how it's different from museums. A museum is curated. Museums are top-down from someone who is probably- people who are, you know, scientists or have degrees in museum creation. The whole point of the museum is not to provide a space for people to explore in that way. Although I obviously, you know, fancy museums are moving toward that direction . . . but in these makerspaces and [City Community Lab], you know—the whole point of the makerspaces is bottom-up, what the members want to experiment with. And citizen science as opposed to introducing the citizen to what science does. I think that's what museums do. (Focus Group Interview, 8/11/2020, 00:52:02)

Jerome's point of view was that the opportunity to pursue a project of personal interest is a consequence of the laboratory's organizational structure. He juxtaposed museums and community laboratories to reinforce his perspective that community laboratory priorities are born out of members (bottom-up) rather than set by the organization. Given his apparent familiarity with makerspaces, Jerome conceptualized community laboratories as parallel to makerspaces in that members have opportunities to access resources as well as participate in an array of community- and self-defined activities. Beyond our consistent observations of community laboratories prompting growth along personal interests, Jerome brought up that the space was also a place where participants could engage the local community—an outward orientation for science learning and practice, a point that resonated strongly with what we observed with Mariah.

Like Mariah and Jerome, Chanah took on projects that enabled her to pursue areas of personal and professional interest. As a long time maker, Chanah had significant experience in bridging the crafts with digital technologies to produce artistic objects that were reflections of her personal interests. When working with Comunidad Lab Space, that expanded to include the life sciences and public health so that she could address issues surrounding the ongoing COVID-19 pandemic. She leveraged Comunidad Lab Space's resources and her own knowledge to empower the community, as she described:

> Most of us are from ag[riculture] worker families, and so his whole issue with Covid and the lack of PPE [personal protective equipment], it's been huge. So one of our biggest journeys this summer—spring actually, we started in April—is we've been surveying field workers and developing PPE and testing it in the field and just doing for us what's a massive PPE drive . . . and we've actually collaborated writing to the governor and had testing stations put into [the community] that weren't there. (Focus Group Interview, 8/11/2020, 00:37:35)

Chanah used the resources she had at Comunidad Lab Space to address what she observed to be an urgent need for PPE in her community of agricultural field workers. Drawing on what she learned about the transmissibility of the virus and measures that could reduce it, she led a campaign to research, develop, and test PPE in the region. Our assessment of this example, which coincides with our observations of Mariah and Jerome's experiences, illustrates that the community laboratory promotes a sense of agency within its members and empowers them to use their laboratory skills and the laboratory's resources to lead socially relevant endeavors.

Overall, these cases show that while community laboratories often start as access points for intellectual and material resources to carry out life science work, they can result in myriad shifts that expand beyond the novice to expert dichotomy. These can include leadership roles, wherein learning can be enacted in service of authentic practice (e.g. facilitating a workshop, mentoring others, designing a research project, leading a PPE effort, etc.). Learning in these spaces seems to precipitate transformational growth that includes more than obtaining life science knowledge and skills to enhance academic and professional growth: it also includes a shift from consuming learning to becoming an agentic producer. Furthermore, our case studies show that productivity moves from being self-oriented to addressing others and the community.

4. Discussion

Community laboratories as biomakerspaces

We leveraged and now revisit a constructionist learning activity design metaphor of "low floors," "high ceilings," and "wide walls" used to describe makerspaces (Papert, 1993; Peppler and McKay, 2013; Resnick and Silverman, 2005). We observed that community laboratories provide, in addition to technical and logistical accessibility, access to communities of expertise that reduce the knowledge threshold for participation—the so-called "low floors" that have also been observed in makerspaces. We observed that participants were able to get involved (i.e. afforded legitimate participation) in the laboratory right away, sometimes with little to no background in the life sciences. This is remarkable given that the field is rife with technicalities (Peretó and Porcar, 2021) and high failure rates (Goodwin et al., 2021; Maltese et al., 2018) that can make participation frustrating and inaccessible to novices. However, despite being able to enter activities right away, members reported growing into fuller participation over time as reflected in their increasing ability to navigate the space, its resources, and the knowledge needed to engage productively.

We also found that after initial practice, laboratory members had opportunities to engage in sophisticated life science projects, a characteristic captured in the metaphor of affording "high ceilings" (Papert, 1993). This was illustrated both in the type of projects members carried out and the range of learning practices with which they engaged, including the development of bioprinters to grow cells, biosensors to detect local water contaminants, and PPE to reduce community exposure to COVID-19. Further studies and longitudinal approaches are necessary to assess the extent to which community laboratories enable sophisticated pursuits in the maker sense. Given that this requires mastery across a complex and often intersecting set of understandings, skills, and practices, the question requires additional consideration of how biological design and construction is consistent with or distinct from making involving inanimate materials and what unique approaches might be necessary to support learners in reaching those heights.

We also considered the flexibilities that exist to allow members to pursue diverse "styles" or trajectories when participating, corresponding to the notion of "wide walls" (Resnick and Silverman, 2005). This was reflected in participant accounts that consistently illustrated how the spaces afforded opportunities to apprentice into a variety of activities that were framed as competitions, collaborations, internships, and research studies. We attribute this to what one focus group member described as a "bottom-up" approach wherein the organizational priorities emphasized the interests of its members.

One distinction emerged—which was evident in participation that had both personal and social relevance (e.g. carrying out social science survey studies to gather community perspectives about

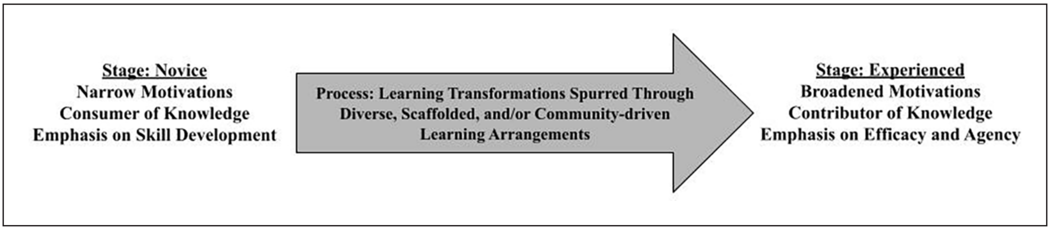

Figure 3. Community laboratory learning and transformational growth.

synthetic biology). While the pursuit of personally and socially relevant interdisciplinary projects is not unique to STEM or makerspaces, the organizational arrangements and resource allocations that enable this type of engagement are arguably more difficult to achieve in the life sciences. For example, designing a personalized robotics or computer science project involves processes and inanimate objects that can be blackboxed to reduce complexity and enable efficient production even by those with less insight or knowledge about the underlying technical processes. In contrast, biological materials require careful and often prescribed handling techniques, or may behave unpredictably, and learners need to be attuned to these specialized processes and potential adverse impacts in the environment. The life sciences are therefore notoriously difficult to personalize. By providing a gamut of biotechnology resources that span multiple domains and learning arrangements, community laboratories enable learners to eventually lead their own pursuits. Because the resources and underlying learning processes coalesce in community laboratories to enable participation that is personalizable and reflective of the individual and their local community, we extend the previous metaphor to include the concept of "deep roots," learning that is inextricably tied to the community.

Spaces for learning and transformational growth

We also considered community laboratory practice in the context of active learning. Our observations suggest these spaces support practice and transformational learning that cuts across inquiry, problem, and design-based perspectives (NGSS Lead States, 2013; Razzouk and Shute, 2012; Sheridan et al., 2014). Our case examples reveal growth that is marked by several characteristics including: (1) broadened motivations for participation, (2) participation shifts from primarily consumers of knowledge and ideas to serving as a contributor of one or both, and (3) increased efficacy and agentic practice (shown in Figure 3).

We believe these outcomes are the result of more than just access to material and intellectual resources, but rather structures that coalesce to shape learning (Cigarini et al., 2021; King et al., 2018; National Research Council, 2009). Common threads in our case studies revealed that these outcomes may be mediated by interpersonal scaffolds that were arranged using structures (e.g. apprenticeships, cooperative collaborations, mentorship, etc.), yet all shared the thread of being situated in personalized yet authentic acts (Anderson et al., 1996; Brown et al., 1989). The cases we examined showed instances where members had opportunities to conduct personal experiments, design unique tools, or carry out technical tasks to support the pursuits of others, all of which required varying degrees of distinct sense-making and knowledge construction to progress. In the case of Arunav and Harold, we observed that space resources and learning arrangements enabled both youths to participate in activities that were suited to their relative expertise and provided the necessary support structures (e.g. collaborations, mentors, etc.) to engage with relatively sophisticated tools and practices. Beyond this, the spaces supported sustained personal growth as each youth shifted toward more independent and agentic participation as they pursued investigations that were novel, open-ended, and authentic to science practice, features made possible by the space's available material resources. For these youths, the community laboratory played a role as a critical access point that not only supported participation and interest beyond what was available to them in their schools, but that spurred transformative growth over time.

Engagement across disciplinary genres and practice, such as that reflected in our survey results, is owed in part to the interdisciplinary material resources available in community laboratory spaces (e.g. incubators, Petri dishes, 3D printers, microcontrollers, and laser cutters). Having access to these resources and to the community of knowledgeable mentors and peers, we believe, is an instrumental first step in supporting legitimate participation in education experiences that prioritize authentic life science practice (NGSS Lead States, 2013). Our examples showed instances where members took on roles that situated learners in relation to others (e.g. an apprenticing new member who was supporting a laboratory manager, or an instructor teaching a new group of students after having previously mastered a course). This suggests that scaffolds in community laboratory spaces can take on social and interpersonal interactions to support the unique and cross-disciplinary life science activities that occur in the space. Insights on socially mediated scaffolds could inform learning in other informal learning environments where modern life science activities have been difficult to implement. Our observations motivate additional examination of how interpersonal scaffolds support life science activities that cut across academic disciplines and occur in informal learning environments.

5. Conclusion and future directions

A central aim of this study was to better understand community laboratories as nascent informal learning environments for the life sciences through the experiences of laboratory members themselves. Our study suggests that community laboratories are successful in part because of the organizational structures used to make material and intellectual resources meaningful, flexible, and accessible. This insight provides an important starting point for understanding contemporary approaches to life science at informal learning sites, a field where much more remains to be done.

There are limitations to our study and some key areas that warrant further examination. First, more work needs to be done to understand the extent to which these spaces are inclusive. Our survey data showed a high degree of diversity in age and gender distributions, but this was not present with respect to race, where small percentages of participants who completed the survey were African-American (9.6%), Latinx (6.8%), or bi-racial (5.5%). This is important in the United States where STEM education is traditionally rife with demographic-based inequities. While focus group participants were representative across age demographics and by proxy career trajectories, we did not specifically ask about educational attainment or income. Inclusiveness has been a persistent challenge in STEM education (Barton et al., 2017; Dougherty, 2012; Kye, 2020); given that community laboratories are relatively nascent, there is an opportunity to address or even preempt issues related to parity in these areas.

Second, more work could be done to understand what is defined as knowing and doing in these spaces and whether that correlates with or could potentially expand the accepted range of these definitions in the life sciences and making (Vossoughi et al., 2016), areas where there are opportunities to broaden participation. This should include insights on how material resources and organizational structures (such as interpersonal scaffolds) come together in community laboratories to achieve personalization that is transdisciplinary (Groth et al., 2020).

Given the growing impact modern life science biotechnologies and practices have on myriad industries, community laboratories may play a critical role as informal learning environments in supporting STEM education priorities for the twenty-first century. This includes efforts to inspire innovation, support occupational attainment and, importantly, inform public literacy, perspectives, and decision-making. This research represents an early stride in the United States toward understanding how community laboratories, their organizational features, and their impact on learner growth, uniquely contribute to those goals and in a geopolitical landscape rife with debate about how contemporary life sciences will flourish—but where education practice has yet to make mainstream inroads to supporting the public awareness needed to do so productively.

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Supplemental material

Supplemental material for this article is available online.

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