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Intersecting Networks Supporting Problem-Based Invention Education

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ABSTRACT

One educational approach aligned with problem-based learning (PBL) is invention education (IvE). Both PBL and IvE place an emphasis on resolving practical problems experienced by real people while engaging students in hands-on learning. In this interactional ethnographic study we examined the networks that supported a high school team and their teacher, as they worked to invent a solution to a real-world problem students identified in their community. Data sources included video and documentary data of the team's work generated by a student-historian during an invention education project as well as Zoom-facilitated ethnographic conversational interviews conducted with the teacher and the student-historian over five months the following year. We uncovered local, local-national, and national supports that impacted the invention education process of the team. Through ecomap, discourse, and domain analyses we demonstrate how supports at multiple levels of the educational ecosystem create opportunities for students and teachers to engage in meaningful, real-world problem-based projects. We argue that varied people and organizations can contribute to innovative PBL and IvE, thus aiding the narrowing of diversity gaps in the fields of invention, engineering, STEM, and problem-based learning more generally.

Keywords: Problem-based learning, invention education, interactional ethnography, networks, mentors

Intersecting Networks Supporting Problem-Based Invention Education

Across the 15 years of the IJPBL publication, authors have presented many ways of conceptualizing, implementing, and studying problem-based learning (PBL). One of the more recent educational approaches for the large PBL umbrella is invention education (IvE; Invention Education Research Group [IvERG], 2019). Both PBL and IvE focus on solving real-world problems and engaging students in active hands-on learning (Chian et al., 2019). Many of the fundamental principles of IvE, such as empathy, engagement, and iterative and recursive processes of learning, are also consistent with those of problem-based education (IvERG, 2019). Both approaches revolve around creating solutions for ill-defined, real-world problems and involve educators in the role of facilitators working with students over time in non-linear, creative, transdisciplinary problem-solving in formal and informal educational settings.

Working with students on ill-defined problems presents a range of challenges for the educators. One of the challenges often cited in the literature is the need for teachers to have knowledge of multiple intersecting disciplines in a PBL environment (Committee for the Study of Invention, 2004; Ertmer et al., 2014; Ertmer & Simons, 2006). However, teachers, especially at the secondary level, usually specialize in discrete disciplines, such as math, biology, or arts and design, and rarely have opportunities to work and learn across disciplines (National Research Council, 2014). Given that no teacher can be an expert in all disciplines, PBL and IvE educational approaches call for a shift in conceptualizing the work of teachers not as knowers or transmitters of knowledge, but as co-learners alongside students (Committee for the Study of Invention, 2004; Sawyer, 2015). In re-envisioning their roles as co-learners and facilitators, teachers often need to seek expertise beyond the school and from across disciplines to support their students' (and their own) work on ill-defined problems. Scholars working in the fields of PBL and IvE have pointed to the need to understand and support the educators who guide their students through the nonlinear processes of PBL (e.g., Ertmer & Park, 2007; Zhang et al., 2019). However, to date we have found few studies focusing on the ways people and organizations within and beyond school can support teachers and contribute to IvE and PBL.

To explore what networks of expertise and resources teachers and students utilize as they work on ill-defined invention problems, we examine who supported a high school invention team and their teacher, and in what ways, as they were working to invent a solution to a real-world problem students identified in their community. In collaboration with the teacher, Katrina Hull, and Jazmin Morales, a student from the high school invention team, we elucidate the often-invisible ecosystems impacting student and teacher opportunities for learning, solving real-world problems, and sharing their work locally and nationally. The research question guiding the study presented in this paper is: What are the networks supporting a high school InvenTeam?

The study draws on a 2-year collaboration between a research team at the University of Central Florida and a teacher and a high school student-historian from an InvenTeam™ in Oregon. The McKay High School (HS) InvenTeam worked on inventing an adaptable cup for people with dysphagia, a medical condition which makes it difficult to swallow. The adaptable cups the McKay HS InvenTeam developed enabled users with dysphagia to adjust and control the flow of liquid based on the user's swallowing capacity. The McKay HS InvenTeam developed two cup prototypes: a mechanical version which required the user to twist a component of the cup to adjust the flow of liquid, and an electronic version in which the flow of liquid was controlled by the press of a button. The team presented their prototypes at the Massachusetts Institute of Technology (MIT) in June of 2019.

While working on their invention during the 2018-2019 academic year, the InvenTeam generated video records and photographs as well as a historian notebook documenting their inventing activities. In 2020, the university-based researchers joined the teacher and the student-historian over Zoom to discuss their work and uncover what support the InvenTeam had or needed to invent the cup and travel to MIT to showcase their invention. This paper focuses on the three levels of support the teacher and the student-historian identified as we co-researched their InvenTeam year over a period of five months of weekly Zoom meetings.

Before proceeding to the theoretical framing, methodology, and analysis of the data, we provide contextual information about the Lemelson-MIT program (LMIT), which sponsored the McKay HS's InvenTeam.

Context

LMIT and the McKay High School InvenTeam

The LMIT Program at the Massachusetts Institute of Technology (MIT) and its principal sponsor, the Lemelson Foundation, are committed to helping young people around the U.S. become inventors capable of addressing current and future problems in the world. The LMIT Program focuses on helping "thousands of students and educators learn to invent" and provides professional development programs and materials for IvE (Lemelson-MIT, n.d.).

One of the sustaining LMIT programs has been the InvenTeam™ initiative. Each year for the past 17 years, up to 15 high school teams around the nation receive a grant of up to $10,000 for materials, research, and learning experiences to design and build technological solutions to real world problems. LMIT supports the InvenTeam invention processes throughout the year by setting milestones, monitoring team progress, communicating with the team, and facilitating connections with Master Teachers who had led InvenTeams previously and have committed to supporting new generations of IvE teachers. The InvenTeam experience culminates at MIT in June, when all teams come together at the end of the year-long project to showcase working prototypes of their inventions. In 2018, a team from McKay HS in Salem, Oregon received a grant of up to $10,000. They are the focus of this study.

McKay High School InvenTeam's Problem for Invention

The McKay HS InvenTeam's project focused on inventing an adaptable cup for individuals with dysphagia. A student on the team learned about the problem during the previous school year when they had met with an occupational therapist through the MESA (mathematics, engineering, science, achievement) club at McKay HS. The occupational therapist explained that individuals with dysphagia require the use of a special cup because of their limited ability to swallow. The therapist also shared that many patients were not comfortable using the cups currently on the market since they did not have adaptable flow and most looked like child sippy cups, making them unappealing for adult users. When the student who had participated in MESA joined the InvenTeam, they shared what they had learned about dysphagia the previous year. The InvenTeam chose this problem as the focus for their invention. The McKay students set out to design a better cup with an adaptable flow system. Figure 1 is a picture of a typical cup that was available on the market and Figure 2 represents the cups the McKay HS InvenTeam invented.

Figure 1. A typical sippy cup for dysphagia

Figure 2. The final two cup prototypes the students designed

The student-historian Jazmin Morales Rodriguez, the 5th co-author, documented the team's invention activities. She, along with the teacher Katrina Hull, the 4th co-author, met with the research team to help us explore the supports the team needed to accomplish their goal and develop a prototype to address the problem.

Before providing an analysis of the kinds of supports the teacher and the team needed, we ground our study in the literature on IvE and PBL. In addition to reviewing arguments about the challenges faced and the support teachers and students need for PBL opportunities, we briefly introduce IvE and the ways it is similar to and different from PBL. In subsequent sections, we document our methodology and analysis, focusing on three types of supports. We showcase two of the supports from different levels of the support systems ecomap we developed in collaboration with the teacher and the student-historian—the McKay HS InvenTeam insiders on our research team.

Grounding in the Literature: Invention Education in the Context of Problem-Based Education

Problem-Based Learning and its Challenges and Supports for Teachers and Students

Problem-based education is a pedagogical approach that engages students and other actors in integrated learning around real-world problems (Lu et al., 2015). In PBL environments, learners work collaboratively to co-construct an understanding of complex issues with the goal of developing possible solutions to ill-structured problems (Bridges & Imafuku, 2020; Chian et al., 2019). The transdisciplinary nature of PBL can be a challenge for teachers to implement in the current system of education where disciplines are separated into different departments (Sawyer, 2015). Teachers, especially at the secondary level, have developed specialized subject knowledge (Park & Ertmer, 2008) and therefore may need support in seeing the interconnectedness of the domains necessary to engage in PBL (Nikitina, 2006). Additional challenges include teachers transitioning to the role of facilitator (Ertmer et al., 2009; Park & Ertmer, 2008) while students become more accountable for their own learning (Glazewski & Ertmer, 2010). Research has also indicated that within PBL and IvE environments, teachers can face challenges with classroom management and addressing mandated standards (Moore et al., 2019; Zhang et al., 2019).

The challenges in PBL have also garnered research on ways of addressing those concerns. Much of the research that addresses support for teachers in PBL focuses on the professional development programs aiming to prepare teachers to implement PBL effectively (Asghar et al., 2012; Ertmer et al., 2014). Researchers who study professional development programs and their impact in preparing teachers to work in PBL settings have found that teachers are more knowledgeable and confident in implementing PBL when they can access a range of support within the school and through professional development. Ertmer and colleagues (Ertmer et al., 2009; Park & Ertmer, 2008) demonstrated that teachers in PBL settings are more successful when they have access to strong mentors and coaches, regular professional development opportunities in PBL implementation, a shared vision within the school with clear goals and benchmarks, and a supportive administration.

In addition to examining the challenges teachers face in PBL settings and the supports PBL professional development provides, scholars have begun exploring what networks and resources teachers need to engage students in working with ill-defined problems (Baker-Doyle, 2014; Herman et al., 2019; National Academies of Sciences, Engineering, and Medicine, 2015). For example, focusing on the teaching of science, Shanahan & Bechtel (2020) explored scientist-teacher collaborations and discovered that both the teachers and the scientists learned about science and teaching when they worked with each other as partners. The authors pointed to the need for collaboration in which teachers and scientists both bring and share expertise, rather than one acting as a sole expert. Other researchers have also explored how people, resources and expertise from outside school can support teaching and curriculum design responsive to real-world problems and diverse workplaces (Bopardikar et al., 2020; Navy et al., 2020).

Emerging literature on outsiders supporting science teaching demonstrates the potentials and impact of outsider expertise on students and teachers (Navy et al., 2020). More studies are needed to explore the often-invisible networks teachers and students can build or call upon to engage in meaningful and impactful problem-solving and inventing processes. IvE, like PBL, is a complex learning process co-constructed by teachers, students, and many other actors involved in the ill-defined problem-finding and problem-solving activities.

Invention Education: One Approach to Problem-Based Learning

Invention Education (IvE) is an educational approach that promotes early and repeated exposure to invention, engagement in invention-oriented activities, and transdisciplinary ways of learning, thinking, and working within and beyond STEM (Committee for the Study of Invention, 2004; Couch, et al., 2019). In a White Paper, members of the Invention Education Research Group (IvERG, 2019) defined IvE as "deliberate efforts to teach people how to approach problem finding and problem solving in ways that reflect the processes and practices employed by accomplished inventors" (p. 1). IvE grew out of calls to address the need for more diverse inventors who can respond to increasingly complex problems in local and global communities (Cook, 2019; Couch et al., 2018; National Academy of Sciences et al., 2011). Invention education, similar to PBL, emphasizes the iterative and recursive processes of identifying real-world problems and developing new, unique, and useful solutions to those problems (Couch et al., 2019).

IvE is open-ended, transdisciplinary, and usually team-based. It incorporates concepts from PBL (Merritt et al. 2017), the maker movement (Maaia, 2019), STEM (Calabrese Barton & Tan, 2019), and engineering design (Mentzer et al., 2015; Perez-Breva, 2016; Petroski, 2018). The content associated with IvE is represented in many disciplines, including K–12 national education standards in English language arts (National Governors Association, 2010a), science and engineering (National Research Council, 2014), mathematics (K–12 Computer Science Framework, 2016; National Governors Association, 2010b), and 21st century learning (IvERG, 2019; Sawyer, 2015; Trilling & Fadel, 2009). Although much of the content students encounter during IvE experiences can be linked to K–12 national standards for different disciplines, there are no specific standards to guide IvE efforts. IvE emphasizes integration across disciplines and does not easily fit into the current silo-bound system of K–12 education (National Research Council, 2014; Sawyer, 2015).

In IvE, akin to PBL, teachers are the facilitators of shared, co-created, and applied knowledge (IvERG, 2019; Zhang et al., 2019). However, teachers are not alone in structuring and facilitating the invention processes and learning for their students and themselves. IvE approaches to PBL explicitly emphasize community involvement and working with mentors beyond the school. The network of mentors and adults from various industries involved in the learning process is one of the defining features of IvE (IvERG, 2019). While PBL and IvE have much in common, IvE's emphasis on outside mentors, intellectual property, and prototyping, among other characteristics demonstrated in Figure 3, makes IvE a unique approach to problem-based education.

As demonstrated in Figure 3, both PBL and IvE begin with authentic problems to stimulate learning. PBL and IvE both focus on students building content knowledge and skills across disciplines. Engaging students in hands-on experiences, both approaches create opportunities for authentic application of knowledge to solving real-world problems. In PBL and IvE, teachers facilitate small groups of students

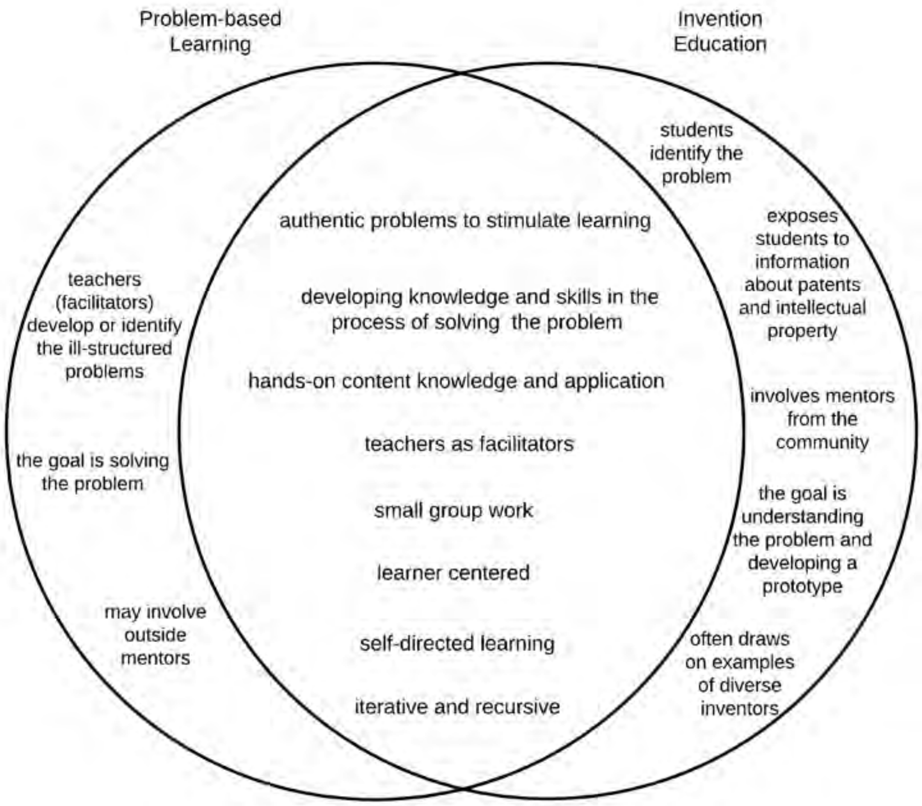

Figure 3. Venn Diagram Comparing PBL and IvE

working collaboratively. Both approaches are learner-centered and involve individual and group-driven self-directed, iterative, and recursive learning processes.

Though similar in many ways, Figure 3 also presents the differences between the two approaches. In PBL, teachers often develop or identify the ill-defined problems students investigate. In IvE, the students, not the teachers, identify the problems through dialogues with members of the community. IvE emphasizes the importance of expertise and mentors from the community and industry. The goal in PBL is to solve the problem, whereas in IvE the goal focuses on developing a working prototype of a solution. To arrive at the solution, teams and individuals engaged in IvE usually begin by devoting time to understand the nature of the problem. IvE often utilizes examples of diverse inventors to inspire and inform student collaborative processes of problem seeking and prototype development. The focus on invention in IvE also exposes students to information about patents and intellectual property. Both IvE and PBL engage students in complex processes of solving ill-defined problems with the support of teachers who act as facilitators of the learning process but accomplish this in different ways.

The literature we presented in this section demonstrates some of the challenges PBL and IvE teachers face and the support they may need. Before proceeding to analyses of the supports we uncovered in our collaborative work with the teacher and student-historian from the McKay HS InvenTeam, we present our overall research approach grounded in ethnographic epistemology.

Research Design

Interactional Ethnographic Foundations

This study is guided by interactional ethnographic epistemology (Green et al., 2012; Skukauskaitė & Green, 2023) and seeks to understand who participates and supports IvE, in what ways, when, where, with whom, for what purposes, and with what outcomes or consequences for a variety of actors engaged in PBL processes (Bridges et al., 2012; Green et al., 2020; Green & Bridges, 2018). Interactional ethnography (IE) explores how people co-construct meanings and patterns of everyday activity in and through interaction in particular cultural groups (Castanheira et al., 2000; Skukauskaitė

& Green, 2023), such as the McKay HS InvenTeam whose work we researched. Starting with socially and culturally significant references group members signal in their discourse (Bloome & Egan-Robertson, 1993; Kelly & Green, 2019), IE researchers examine the multiple layers of contexts insiders make relevant for understanding their work (Skukauskaitė & Girdzijauskienė, 2021). The contexts may include social, political, economic, and other influences (Green & Heras, 2011) as well as contexts participants invoke and co-create through discourse within the group (Bloome et al., 2005; Skukauskaitė & Girdzijauskienė, 2021). IE draws researcher attention to particular interactions and the ways these interactions are situated in multiple contextual layers, networks, and influences within particular moments and across time.

Drawing on the larger IE program of research on IvE (Couch et al., 2018; Couch et al., 2019), in this paper we focused on networks of support the teacher and student-historian discursively made relevant. To uncover the support networks insiders marked as significant for their IvE process, we created the ecosystems map. Following the ethnographic logic of inquiry, we also conducted domain and taxonomic analyses (Spradley, 1980/2016) to demonstrate the supports at each level of the ecosystem. Participant discourse from the video records and co-participatory analyses provided evidence for telling cases of supports at different levels of the ecosystem.

Data Sources

The records from the McKay HS InvenTeam included videos, photos, and narrative summaries of all team activities during the 2018-2019 year. Throughout the InvenTeam year, the team historian documented the team's progress by keeping a "historian's notebook." The historian's digital notebook, a password-protected folder containing Microsoft Word files, was our primary source of data. The notebook was broken down into entries using separate Word documents for each day the team met. There were 56 documents in the historian's notebook. The majority of the entries had links to videos with captured activities from the day. In total, the digital notebook included 203 video files as well as brief reflections the historian wrote for each day. Additional data sources included 22 hours of recorded conversations with the teacher and the student-historian who joined the university-based research team to explore the records during weekly Zoom meetings over five months.

Research Site and Participants

The McKay HS InvenTeam was embedded in a public high school in Salem, Oregon. The Oregon Department of Education demographics for the 2018-19 McKay HS indicated 64% of the students who attended McKay HS were Hispanic/Latino, 24% were White, 4% were Native Hawaiian or Pacific Islander, 3% were Asian, 2% Black, 2% multiracial, and less than 1% identified as American Indian. More than 95% of the students at McKay HS had been identified as economically disadvantaged and 56% as college-going (Oregon Department of Education, 2020). There were 11 students on the McKay HS InvenTeam for the 2018-2019 school year. Nine were in the first year of high school and three were seniors. Eight of the students on the team identified as female. Seven of the female students identified as Latina and one as an Asian American. Of the three male students, one identified as Latino and two identified as White. Students volunteered to participate on the team after an informational meeting about the LMIT InvenTeam grant opportunity. 30 students attended the informational meeting and 11 self-selected to be a part of the team.

McKay HS is located 47 miles from Portland, Oregon, where the Lemelson Foundation is located. Representatives from the Foundation typically attend the culminating showcase event at MIT, but McKay HS's proximity to Portland gave students the unique opportunity to interact with members of this non-profit organization on more than one occasion. Students from the McKay HS InvenTeam presented their prototype at the Lemelson Foundation in preparation for their trip to MIT.

Problem-Based Learning Experiences on the McKay High School InvenTeam

The McKay HS InvenTeam's focus on inventing an adaptable cup for people with dysphagia provided students an opportunity to engage in authentic problem solving of an ill-defined problem. In inventing the two prototypes of the cup, students developed epistemological content knowledge across disciplines, including physics, mathematics, engineering, communication, and the English language arts. They also learned skills of communication, presentation, budget management, accountability, and teamwork (among others), and utilized those skills in multiple ways (e.g., presenting to different audiences, budgeting and receipt tracking, division of labor, collaboration). Students learned invention, engineering, design, communication, and collaboration in the process of experiential and just-in-time learning opportunities.

Consistent with PBL principles, the McKay InvenTeam teacher, Katrina, facilitated student invention and learning processes and learned alongside the students throughout the InvenTeam year and beyond. Through the hands-on, self-directed, iterative, and recursive learning processes of problem-based education such as PBL and IvE, students and the teacher collectively co-constructed learning opportunities for themselves individually and the team as a whole. For example, one student who had never heard of

Computer-Aided Design (CAD) learned the software and the digital-to-physical design process in CAD, another learned coding, while the third learned soldering. Another student learned 3D printing, a bilingual member of the team enhanced their translation and communication skills, and the team student-historian, Jazmin, learned and utilized ethnographic research processes, including data management and conversational interviewing. The IvE process was learning-centered, self-directed, and collaborative, enabling team members to develop a variety of knowledge and skills and accomplish the goals as a team.

Analysis Processes

Our first analytic pass (Skukauskaitė, 2019) through the records focused on documenting the InvenTeam's work over time. We did this by indexing the historian's notebook and video recordings, then creating event and subevent maps (Green & Wallat, 1981) of the team's daily activities. The second analytic pass involved creating an ecomap of the supports for the invention project. Frequently used in counseling and social work, the ecomap is a tool used to visually represent ecological systems and their impact (Paladino & Kocet, 2020). Because the ecomap is customizable, made to be bidirectional, and used specifically for seeing the individual's relationship with their sociocultural environment (Paladino & Kocet, 2020), it proved a useful tool to display the multiple social networks and support systems that affected the InvenTeam as a unit. Through conversational ethnographic interviewing with the teacher and the student-historian as insiders (Skukauskaitė & Sullivan, 2023), we produced an ecomap of three interrelated levels of support the McKay HS InvenTeam utilized in their invention process.

In the third analytic pass we identified telling cases for each level of support. We searched through video, historian's notebook, and ethnographic conversation records to develop the telling cases of supports InvenTeam insiders had marked as socially significant (Bloome & Egan-Robertson, 1993). Drawing on the insider discourse, the fourth analytic pass involved creating domain and taxonomic analyses (Spradley, 1980/2016), showing not only what the support was, but also how it was instrumental to the McKay HS InvenTeam.

In the next section, we introduce the ecomap and analyze telling cases of supports at different levels of the ecosystem supporting IvE at McKay HS.

Findings: Uncovering the Ecosystem

In education research, ecosystems have been used to represent complex environments and processes (Weaver-Hightower, 2008). By conceptualizing networks of support as ecosystems, we show the complex and interdependent nature of the relationships between actors, organizations, and the team (Weaver-Hightower, 2008). Figure 4 is an ecomap which identifies the three levels of support: local, national, and a level we named "both" since these networks or processes functioned at both levels. We used different colors

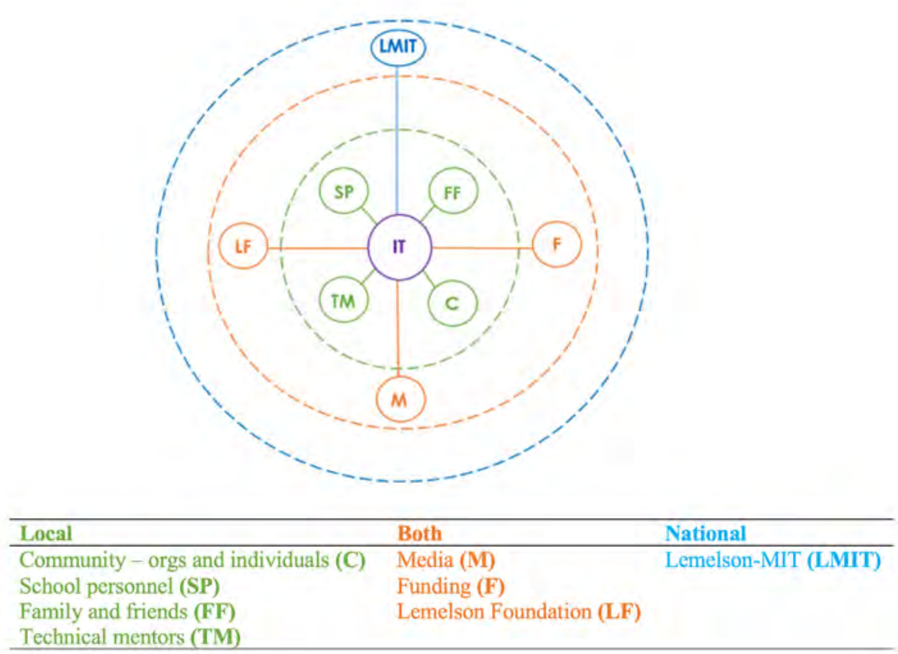

Figure 4. Levels of Ecosystems Supporting IvE

to represent the different levels of support: green indicates the local supports, blue indicates the national supports, and orange indicates the supports that were both local and national. The lines around the levels are dotted, not solid, to signal the interrelationships and permeability among the levels.

The legend under Figure 4 indicates the kinds of people, organizations, and processes McKay HS InvenTeam members marked as important supports for their invention process. Local networks of support refer to the people and organizations in the students' and the teacher's immediate environment, and include families and friends, technical mentors, and school personnel. Media, funding, and the Lemelson Foundation supported the team on both local and national levels. In our collaborative analysis meetings over Zoom, the teacher and the student-historian placed the LMIT program at the national level.

In the following section, we present telling cases of support from the local and the national levels of the ecomap. Together, the supports at the different levels reveal how outsiders can help create, facilitate, and sustain opportunities for high school students and their teacher to work on developing an invention to solve a real-world problem.

Supports for Invention Education: Telling Cases of Local and National Supports

Local Ecosystem: Outsiders Providing Technical Support

One of the key local supports for IvE includes technical mentors. In IvE, technical mentors are people from the community who work with the team to accomplish student goals of invention. Mentors provide the technical expertise that is not available to the team within the school. In the InvenTeam we studied, technical mentors worked side by side with the students to support student learning and inventing. The McKay HS InvenTeam had two main technical mentors—the teacher's husband, Tyler[1] , who had an engineering background, and an engineer from Portland, Chau, whom the teacher had met at a previous engineering conference. Here we present Chau's mentoring as a telling case which demonstrates how an outsider can become a key support for the students and teacher engaged in IvE.

Chau joined the team as an outsider in February and, over the course of the semester, became a key resource supporting students in acquiring knowledge and technical skills needed for their invention. Table 1 provides a domain analysis of three kinds of technical support Chau provided students by sharing his engineering expertise, guiding rather than doing, and modeling the engineering design and thinking processes.

The first kind of technical support Chau provided was sharing his engineering expertise with the students, some of whom had no prior experience in 3D modeling and printing, coding, or other engineering practices needed to develop a prototype for an invention idea. For example, on his first day with the students, Chau sat next to two girls who had not used the Arduino hardware or the Computer-Aided Design (CAD) systems before and helped them understand how to work with the systems. Over time, he supported them in creating and printing the 3D model of the cup they were designing. In addition to showing how the systems worked, Chau's engineering expertise also provided support for students working on coding. He did not simply teach coding, but, as the teacher explained, he worked with the students "based on student parameters." Sharing engineering expertise provided the technical support for students to learn 3D modeling, printing, coding, and engineering design.

The second kind of technical support focused on Chau "guiding rather than doing." Instead of completing work for the students, Chau worked with the students to create and execute their designs. One of his first interactions when meeting the team was with a student who had designed the mechanical prototype of the cup and was having difficulty getting the electronics to work as she intended. As she explained her idea to Chau, he listened intently and, at the end of the interaction, said he would review the design and let her know if he had any questions. The student hesitantly asked if she could be present for the process. Chau responded by reassuring the student that he just needed time to understand her design so he could help appropriately. In the video-recorded interaction we transcribed in numbered message units (MU; Green & Kelly, 2019; Green & Wallat, 1981), he made it clear that he was there to guide and support, not to do the work for her:

1. I'm not just going to be like
2. here you go and it works
3. no, no, no
4. that's not how it works
5. I'm going to show you what I did to get it there
6. and that'll give you ideas

1 All adult names are real. The teacher co-author had shared an earlier draft of the manuscript with the people named and asked them for their preference to be identified or not. The adults wanted their real names to be used. Giving options to participants is consistent with the ethnographic research practices of giving due credit to the people who contribute to knowledge development.

All students were minors at the time of writing this manuscript, so their names are pseudonyms, except for the student-historian who is the 5th co-author of this article.

Included term	Semantic relationship	Cover term
Sharing engineering expertise Guiding rather than doing Modeling the engineering design process	is a kind of	technical support

Table 1. Domain 1: Technical Support

7. on how you can build your stuff
8. or make modifications to it

In messages units represented in lines 1-2, he negates the assumption he thought the student had—that he would do the work. In line 3, he says "no" three times, strengthening the contrast with her assumption, and in line 4 he states, "that's not how it works." In lines 5-8 Chau explains that the way it would work involves him sharing his thought process of figuring out her design so she can develop her own ideas (line 6) to build or modify her own "stuff" (lines 7-8). By strongly negating through three iterations of negative statements (lines 1-2, 3, and 4) the student's initial assumption that he was there to do the work for her, Chau establishes his role as one of guiding and supporting through understanding the student's needs and design. He is there to support her ideas (line 6) as she builds and modifies her designs, not to advance his own knowledge.

The third kind of technical support Chau provided was modeling the engineering design process and setting expectations of how it works. An interaction recorded on the historian's video (see partial transcript in Table 2) captures a conversation with a student, Lynn (pseudonym), in which Chau shows that the engineering process involves understanding a problem and iterating (building again) with a focus on improvement. Based on his experiences as an engineer, Chau also provides expectations for the development and progression of student prototypes.

This dialogue between Chau and Lynn captures the ways Chau modeled the engineering design process for the students. In MUs 1-9, Chau shares a rule he follows as an engineer. According to this rule (MU 2), the engineering design process involves building a prototype at least three times (MU 4, 6, 8) before showing it to anyone else (MU 9). He emphasizes the importance of understanding the problem through the first attempt at building the prototype (MU 4-5). In the second iteration engineers "try to get it right" by building it again (MU 6-7), while in the third attempt, they "show it" (MU 8-9) to an audience. In explaining this engineering design process, Chau sets the expectation that students will need to build multiple iterations of their prototype before they would be ready to share it with an audience.

Chau sets further expectations for the engineering process by explaining they would "work towards" the student's sketch of the final product (MU 14-16) and the "first couple" (MU 18) prototypes would look nothing like her original sketch (MU 19). Lynn expresses her understanding by responding "absolutely" and "yeah / sure /... / yes" (MU 20, 21, 23) as Chau shares expectations with her. The student demonstrates her understanding of the need to build multiple prototypes when she says, somewhat hesitantly, in choppy, short bursts of speech: "I know / it's going to / maybe not be / cute" (MU 29-33). Chau confirms the student's understanding that in engineering things do not need to be cute—he uses the word "doesn't" twice (MU 35-36), reiterating an agreement they co-developed. He also positions engineering as work (MU 39) and, by identifying himself with that work ("my"), reiterates the importance of the engineering practice of building "ugly" initial products (MU 42). However, in MU 45 he shows that ugly is "part of the beauty of it." Chau explains that building the multiple iterations creates causality between actions and outcomes and allows an engineer to appreciate the beauty (MU 45) in "how much work it takes" (MU 49) to transform something from ugly (MU 42) to "elegant and product ready" (MU 49-51).

In this interaction, Chau exposes the student to the engineering design process and connects it to her sketch and the team's goal of developing the prototype. Chau helps Lynn to recognize that engineering design starts with understanding the problem, and this understanding develops through building. Engineering also involves multiple iterations of building, starting with a sketch and working towards the goal. In the process things may look ugly, but the beauty of the engineering design comes from owning the process and realizing all the work it takes to make something elegant and ready for others.

In explaining and modeling the engineering process, guiding students rather than doing the work for them, and sharing his own engineering expertise, Chau provided the local technical support the team needed to develop their

MU		Transcript	Analytic notes about the engineering process
1.	C	uh	● engineering process has rules,
2.		there is a rule that I have	which may be specific to each engineer
3.		is	
4.		I build it once	● understanding requires trying to build things
5.		to understand the problem	● understanding the problem comes first
6.		and then I build it again	● building things more than once to make sure it works
7.		to try to get it right	
8.		and I'll build it a third time	● iterating more than once
9.		and then I'll actually show it to you	● presenting protype to others is part of the process ● presenting comes after multiple iterations
10.	L	*yeah*	
11.	C	so	
12.		yeah	
13.		so	
14.		what I want to say is like	
15.		your sketch is	● designing starts with a sketch ● starting with where the students are in understanding design
16.		what we're going to work towards	● framing the end goal
17.	*L*	*absolutely*	
18.	C	and the first couple ones	● building more than once
19.		aren't going to look anything like it	● not focusing on the looks of prototype
20.	*L*	*yeah*	
21.		*sure*	
22.	C	good	
23.	*L*	yes	

Table 2. Discursive Construction of Expectations for the Engineering Process

24.		good	
25.	C	so you're taking	• there is a right way to approach the process
26.		the right approach	
27.		to this	
28.	*L*	*yeah*	*student acknowledging the process may not be "cute"*
29.		*I know*	
30.		*its*	
31.		*going to*	
32.		*maybe not be*	
33.		*cute*	
34.	C	oh	
35.		it doesn't	• understanding appearance of a
36.		it doesn't	prototype doesn't matter
37.		have to be	
38.		um	
39.		in my line of work	• positioning engineering as work • invoking work-based expertise ("my")
40.		things	• reiterating that initial products in engineering "are ugly"
41.		just	
42.		are ugly	
43.		uh	
44.		and	
45.		that is part of the beauty of it	• seeing there is beauty to the engineering process
46.		because it	• engineering includes causality ("because") between actions (building multiple times) and outcomes ("the beauty")
47.		then you	
48.		really get an appreciation	
49.		for how much work it takes	• engineering involves appreciating the beauty because of the work that goes into it
50.		to make something	
51.		elegant and product ready	• making something "elegant and product ready" requires much work

Table 2 cont. Discursive Construction of Expectations for the Engineering Process

invention. As the teacher said, "I can't sum up all he did." Over time, Chau became a key resource for the students not only in his technical expertise, but also relationally. As the teacher and the students shared with us, students trusted him and went to him with any kind of small and big problem they encountered throughout the InvenTeam year.

Including technical mentors was an intentional part of the IvE process designed at the national level of the ecosystem and enacted locally. In the next section we focus on the ways the LMIT program provided the structuring which impacted what students, teachers, and their mentors could accomplish in inventing and building human connections beyond school, and in what ways.

National Ecosystem: Lemelson-MIT

In this section, we present LMIT as a support at the national level of the ecosystem. The telling case of LMIT demonstrates how national organizations can provide the overarching supports needed to successfully engage students in IvE. In addition to providing the grant funding, LMIT provided professional development for the teacher, the framework for structuring the InvenTeam year, and opportunities to foster human connections beyond the school. While the team was afforded the flexibility inherent in the problem-based invention process, the framework LMIT provided was instrumental in the success of the McKay HS InvenTeam. Table 3 provides a domain analysis of three kinds of support LMIT provided for the McKay HS InvenTeam as well as all other InvenTeams nationally.

Included term	Semantic relationship	Cover term
Providing educator professional development about invention education Structuring the InvenTeam process Fostering human connections beyond school	is a kind of	National support

Table 3. Discursive Construction of Expectations for the Engineering Process

Professional Development as a Support

LMIT's first support for the McKay HS InvenTeam came in the form of professional development (PD) for the facilitating teacher. She was one of the 35 Excite Award winners whose initial applications for an invention project won them an opportunity for a 4-day LMIT-funded professional development event in Cambridge, MA, in June of 2018. The PD took place at EurekaFest, a four-day event at MIT in which prior year's InvenTeams showcased their inventions. At the event, the Excite Award educators interested in competing for the InvenTeam grants participated in invention-focused PD and received individual feedback on the projects proposed in their initial application. The educators also had opportunities to view and interact with students and teachers presenting their InvenTeam projects.

In a Zoom conversation, the teacher explained how the activities of the PD framed the vision and structure of IvE and modeled ways of providing multiple access points to inventing for diverse learners. Table 4 represents the analysis of an excerpt of the teacher's response to the question, "How did the PD from LMIT support you and the team?" In responding to this question, the teacher talked about her work with the students, signaling how some of this work was a result of her experience with PD on IvE.

In sentence 1, the teacher shared that she "instantly" thinks of time spent in the classroom when asked about the support that LMIT provided. The teacher explained (sentences 2 and 3) that the activities LMIT provided made learning accessible to all students within the "set learning window" (sentence 2) of the InvenTeam meetings. In sentence 4 she juxtaposed LMIT to other PD programs which do not provide activities directly implementable with her own students. The teacher signaled the idea of the importance of access to IvE for diverse students when describing an "entry point everyone could enter and learn" (sentence 4). She called this way of providing equitable access through varied activities a "neat" element of the PD she has received.

Professional development provided by LMIT began by exposing the teacher to the guiding principles of IvE at EurekaFest and remained a consistent support throughout the year. The activities she participated in as part of her own PD became access points for her diverse learners. The PD was a starting point for her and her students to engage in IvE within the structures provided by LMIT for the whole year.

Structuring Support

The second type of national support LMIT provided was the structuring for the InvenTeam year. An example of the structure provided by LMIT, detailed in the internal reports and explained by the teacher in our research meetings, was the support of the Team Access Site (TAS). Domain analysis in Table 5 indicates five kinds of structuring in TAS the teacher found helpful for her facilitation of student engagement in inventing.

The teams were granted access to the LMIT team access site at the start of their InvenTeam year, and the site was monitored by LMIT staff. Within the TAS, the teams had all the relevant documents for supporting their work and reporting their activity and spending. The TAS also contained multiple templates for the team to utilize in planning and conducting their activities, such as reaching out to members of the community and media, fundraising, and developing their presentations. The templates and documents on the TAS site provided necessary structures for the experience of inventing a prototype within a set window of time between late

	The teacher's response	Analytic notes on how the LMIT PD became a support for the team
1.	I instantly think about the time spent in the classroom.	Connecting PD experiences with her own time with the InvenTeam in her classroom (after school)
2.	So, [time] spent in the set learning window.	Understanding how to engage students in learning within a bounded window of time
3.	And they really went through and they found activities that we could do that I felt everyone in the room was able to get something from.	Learning activities she implemented with her own team Seeing how the activities she had learned at PD created multiple access points for her diverse students
4.	Which is not true with PDs across the board.	Comparing to other PDs
5.	So, that was the entry point everyone could enter and learn something, which was neat.	Seeing varied activities of PD as providing multiple points of entry for "everyone" to invention education

Table 4. Analysis of the Teacher's Response

Included term	Semantic relationship	Cover term
Access to a website monitored by LMIT staff Documents guiding InvenTeam work by month Structure for reporting monthly activity Structure for reporting spending Updates from LMIT for monthly activities	is a kind of	Structuring supports through the Team Access Site

Table 5. Domain Analysis of the Types of Structuring Supports Provided Through the Team Access Site

October, when the teams were notified about winning the grant, and June, when the teams traveled to MIT to present their prototypes.

LMIT staff not only monitored team reporting on TAS but also used the site to update the teams with specific instructions and expectations for each month. If the LMIT staff noticed issues such as a lack of activity or insufficient budget spending on team reports, one of the LMIT IvE officers would reach out to the team. The teacher shared that knowing the LMIT staff was monitoring the site "held the team accountable," and this was an important support for her. She appreciated the behind-the-scenes work of the LMIT staff, but those supports were largely taken for granted and invisible to her as she engaged with the students in inventing. At the time, those supports were part of the process, enabling her to focus on the students and the inventing process rather than creating structures for the work to happen. The TAS resources, embedded accountability, and LMIT staff's monitoring and updates from afar were key supports whose importance the teacher understood mostly upon reflection and work with the research team. It was during the research collaborations with outsiders that she reflected on the many forms of structuring that guided and supported her work with the students.

Fostering Human Connections Beyond the School as a Support

The third type of national support that LMIT provided was through the fostering of human connections beyond the school. The structure of the LMIT InvenTeam process became a pathway for building connections with people beyond the school in the local community and nationally. The InvenTeam expectations and guidelines required students to reach out to the community and interact with people, such as elected leaders or members of the media, they would not meet otherwise.

Evidence of LMIT fostering human connections beyond the school is captured in the teacher's description of an interaction between Mr. Gaus, the board chair of a non-profit organization focused on entrepreneurship, and the McKay HS InvenTeam students. The teacher met Mr. Gaus earlier that same year when she was exploring possibilities for fundraising to get the team to MIT in June. He shared several ideas, connected her to professionals with vast experience in fundraising, and became interested in the work the teacher was doing with the students. He came to the Mid-Grant Technical Review (MGTR, a term used by LMIT) in which the students presented their current iterations of the protype. At MGTR, which the teacher and students referred to as the McKay Community Showcase, Mr. Gaus talked with the students and helped them believe that fundraising the money needed for their trip was possible. The teacher explained the impact that his presence and support had on the team:

> (1) He came to McKay Community Showcase [MGTR]. (2) The students remembered him coming up to them and telling them that they would reach their goal and they held onto that. (3) It felt prophetic to the students that this individual knows we are going to get there. (4) They really heard it as truth.

In sentence 1, she used an active verb "came," emphasizing the fact that this leader from the community chose to come to the high school to meet the students and see their showcase. She captured the impact of his interaction in sentence 2 when she said the students "remembered him," how he approached them, and how he helped them believe their goal was possible. She reflected on this impact by sharing that the students "held onto" this belief from then forward. In sentence 3, the teacher explained it felt "prophetic" to the students to hear the certainty of his knowledge that "we are going to get there" in reaching the fundraising goal. She reaffirmed this in sentence 4 when she stated that the students heard his statements as "truth."

The interaction with this one individual from the community is a telling case of how the expectations of fundraising and inviting community members to attend student presentations of their invention prototypes become supports for the teacher and students. When outsiders say and "know" the team can reach their goals, the students take it as "truth" and envision the possibilities for themselves. We chose to focus on Mr. Gaus because he was instrumental in helping students realize that their trip to MIT with their prototype was possible. We also highlighted his contribution because after the InvenTeam year, he continued the interactions with the teacher and invited her students to attend his organization's youth camps. This account demonstrates how one encounter with a person beyond the school can open doors not only to future opportunities but also to student beliefs in themselves and their goals.

There were many such individuals the teacher told us about during our research meetings. They included the city mayor, the director of high schools for the district, leaders from businesses and non-profit organizations, Rotary Club members, representatives from the media, as well as the students' parents, siblings, and extended family members who supported the students and the teacher in many ways. These supports became possible because working with the community and fundraising for the team's trip to MIT were expectations through which LMIT structured and guided InvenTeams to their goals.

Conclusions

In this study, we uncovered intersecting levels of networks supporting a teacher and a group of high school students engaged in developing a prototype to address a real-world problem in their community. In collaboration with the teacher and the student-historian, we discovered the local networks of support included the families and friends of the students and teacher, the technical mentors, the school personnel, and other individuals and organizations in the community. Our telling case focused on the role of the technical mentors, a much needed but often invisible kind of local support. The results of our study support the findings of other studies which have illuminated the role members of the community and families play in supporting students throughout their IvE experiences (Saenz, 2022). More work needs to be done in studying the ways family and community members can support students in the invention process.

The national support we explored focused on the LMIT program, which provided professional development for the teacher, the overall structure for the InvenTeam process, and opportunities for fostering human connections beyond the local school. The intersecting local and national networks of support we identified in the ecomap as "both," but did not explore in this paper due to space limits, included media outlets, funding sources, and the Lemelson Foundation. The three intersecting levels of supports enabled the team to reach their goals of creating their prototypes and traveling to MIT in Cambridge, MA to present their invention.

Our analyses demonstrate a variety of ways actors across the ecosystem can support teachers and students as they work through the iterative and recursive processes of solving ill-defined problems in IvE and PBL. One way of supporting innovative IvE and PBL education is for individuals within and outside the school to engage with students and teachers in identifying, understanding, and exploring multiple ways of solving a problem and inventing a prototype. By supporting teachers' work in facilitating student learning, various actors may provide the necessary expertise to implement IvE and PBL. Teachers and other adults or organizations supporting students in PBL and invention can also validate student development as young inventors through encouragement, working with their ideas, and helping encourage the belief that anything is possible (Saenz, 2022).

Supports at multiple levels of the ecosystem create opportunities for students and teachers living and working in differently-resourced communities to engage in meaningful, real-world problem-based projects that impact both the students and those who benefit from student inventions. Support from varied people and organizations expand the potentials for addressing the gaps in diversity in the fields of invention and engineering (Calabrese Barton & Tan, 2019; Cook, 2019; Saenz, 2022). By recognizing and drawing on the funds of knowledge from students, their families, and their communities (Saenz & Skukauskaitė, in press), educators can support student learning of disciplinary and transdisciplinary knowledge and skills needed for the collaborative, iterative, and recursive processes of inventing and learning (Saenz, 2022).

Invention education and PBL scholars have argued that including community ideas, knowledge, and resources is needed to identify and solve complex social problems (Ashcraft & Breitzman, 2007; Calabrese Barton & Tan, 2019; IvERG, 2019; Saenz & Skukauskaitė, 2022). Our findings demonstrate the importance of teachers drawing from networks beyond the school in problem-based IvE settings. In the field of science education, researchers have begun to pay attention to the role of outsiders in supporting student learning (Bopardikar et al., 2020; Navy et al., 2020). In PBL and IvE, which are usually transdisciplinary and do not fit into the siloed models of education (National Research Council, 2014; Sawyer, 2015), research on the ways outsiders can support teachers and students working on ill-defined problems is only beginning to emerge. Few studies have demonstrated what outside support is needed and in what ways PBL and IvE teachers and students benefit from the knowledge and resources of people and organizations beyond the school.

This study demonstrates the importance and impacts of tapping into the different networks, from the local to national levels. As we add to this nascent field of research on outside support for PBL and IvE, we call on other scholars to attend to the potentials of outside expertise and support in enhancing problem-, project-, and invention- focused learning opportunities for diverse students locally, nationally, and internationally. PBL and IvE are complex and nonlinear educational approaches, and their potentials may be enhanced when tapping into the resources and expertise of people and organizations beyond the educational settings in which PBL and IvE work takes place. Connecting students, teachers and diverse communities in real-world problem solving creates multidirectional opportunities for learning and development of innovation in society.

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Cristina Saenz is the manager of Invention Education at Lemelson-MIT and an adjunct instructor at the University of Central Florida. She recently earned her Ph.D. in Education with a specialization in Inclusive STEM. She completed her Master of Arts in Teaching at Northeastern University and her bachelor's at Rollins College. Prior to earning her doctorate, she was an elementary school teacher in both Boston, MA and Orlando, FL. Her research focuses on examining the life experiences of underrepresented minority students who have participated in invention education. Cristina's passion is engaging diverse students in the invention ecosystem.

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