Editorial: Facilitating Use of Open Hardware in K-12 Schools — Summary of Discussion at the 2024 National Technology Leadership Summit

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The National Technology Leadership Summit (NTLS) coalition is a consortium of 12 national teacher educator associations established in 1999. The NTLS associations met for the 25th invitational technology leadership summit, held at the National Education Association in Washington, D.C., on September 18 – 19, 2025. The presidents of participating associations and other national educational leaders meet for two days of conversations about ways to collaborate across interdisciplinary lines to advance effective use of technology in education. Outcomes from these collaborative efforts can be viewed on the NTLS website (https://ntls.info/ntls-outcomes/). Among other activities, the

NTLS associations jointly publish a peer-reviewed journal, *Contemporary Issues in Technology and Teacher Education*. Each association contributes editors and reviewers relevant to its respective area of expertise.

This report describes recent efforts by the NTLS associations addressing science, technology, engineering, and mathematics (STEM) education to facilitate effective use of makerspaces in schools. The 25th Anniversary of NTLS provides an opportunity to not only report on this specific effort, but also describe the way in which cross-disciplinary dialog at NTLS is translated into collective efforts. This typically begins with a conversation at the summit followed by subsequent collaborative efforts. The sections that follow describe collective efforts to facilitate the use of open hardware in K-12 schools.

The Role of Open Hardware in University Research

The advent of open-source hardware, or open hardware, made possible by affordable fabrication tools like 3D printers and inexpensive microcontrollers has altered the landscape of scientific research. These capabilities have led to progressively more sophisticated open hardware tools for university research (Baden et al. 2015; Pearce 2014, 2017). Open-source tools can replace $15,000 of commercial optics equipment in a university physics classroom with objects printed in-house for $500 using a selection of predesigned components from the open-source optics library (Zhang et al., 2013). Other open hardware tools include simple colorimeters and pH meters, automated titrators, data loggers, and generic control devices for automated assays (Urban 2014). High-voltage power supplies, pressure and mass flow controllers, syringe pumps, multiposition valves, data recording systems (Koenka et al. 2014), and robot-assisted mass spectrometry assay platforms (Chiu & Urban 2015) are other examples of open-source science tools and instruments. Among the benefits of open hardware tools are the following:

1. Significant savings can make scientific research more feasible.
2. Designs developed by users can be customized for a given research task.
3. Construction of scientific equipment can lead to deeper understanding of underlying principles. (Gathering for Open Science Hardware, 2024)

The OpenFlexure Microscope, for example, is an open-source, medical-grade microscope with sufficient image quality for diagnosing parasites and cancerous cells (The OpenFlexure Project, n.d.). This microscope was developed to address significant challenges in microscopy that impact global healthcare. It can be locally fabricated, maintained, and used in remote environments and has been fabricated in hundreds of universities and medical settings worldwide. Open, customizable hardware designs such as the OpenFlexure microscope allow for a balance among speed, reliability, and performance. These advantages are useful in research laboratories (Knapper et al., 2024).

Richard Superfine, the Taylor-Williams Distinguished Professor at the University of North Carolina at Chapel Hill, noted that he could not dedicate a separate $15,000 medical-grade microscope to each laboratory experiment. He also would not be able to customize its proprietary software. In contrast, he can construct and customize a dozen different OpenFlexure microscopes for a few hundred dollars each and dedicate one to a separate experiment in his laboratory (Superfine, 2023). Advantages like these have led to significant growth in the use of open hardware at the university level.

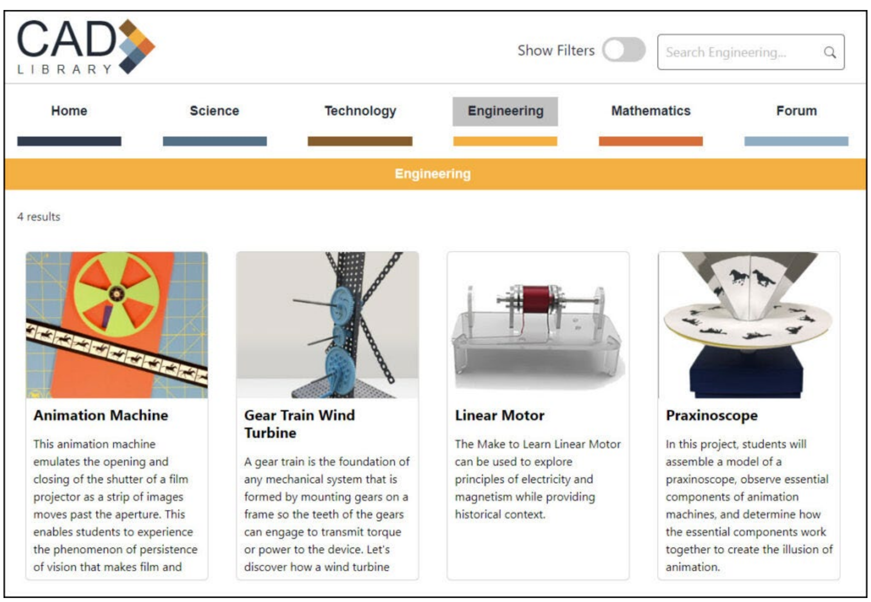
The Status of Open Hardware in K-12 Schools

Use of open hardware is primarily occurring at the postsecondary level (Heradio, et al., 2018). Barriers to adoption of open hardware in K-12 schools include (a) a lack of open hardware designs for schools, (b) a lack of school staff to fabricate open hardware tools and instruments, and (c) a lack of engineering expertise in many schools.

NTLS 2022: Educational CAD Model Library

At the 2022 NTLS meeting in Washington, D.C., the NTLS STEM associations participated in planning for an extension to the *CITE Journal* that could be used to review educational objects as well as academic manuscripts. The NTLS STEM associations used support from an NSF Pathways to Enable Open-Source Ecosystems award (NSF No. 2229627) to establish an Educational CAD Model Library (www.CADLibrary.org; Figure 1).

Figure 1
Educational CAD Model Library



The CAD Library provides a mechanism for reviewing and publishing open hardware designs for K-12 schools. It also encourages development of new open hardware designs aligned with K-12 instructional standards (Bull et al., 2023). This national effort addresses one barrier: development of designs specific to K-12 schools.

NTLS 2023: Engineering Students Fabricate Microscopes for Science Classes

At the 2023 NTLS meeting, the CAD Library curators discussed a strategy to facilitate fabrication of open hardware in K-12 schools. This strategy involved fabrication of tools by engineering students for use in science classes. The group agreed to pilot the strategy using an open hardware design for a 3D printed microscope.

Fall 2023

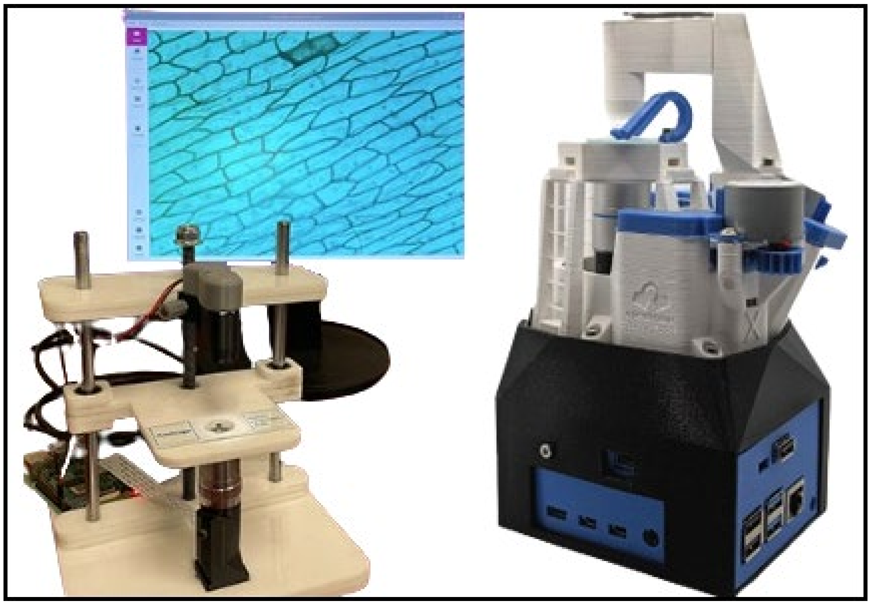
In fall 2023, the chair of the University of Virginia Biomedical Engineering Department, Shayne Pierce-Cottler, created a special topics class for five biomedical engineering students. The students attempted to fabricate an OpenFlexure microscope. They encountered a number of issues and challenges related to both hardware fabrication and assembly and software. Questions posted on the OpenFlexure were typically answered by the members of the OpenFlexure community within a few hours, demonstrating the value of a community of distributed online support. Without this support, the students would not have been successful in replicating the OpenFlexure microscope. It took the university students a semester to replicate the design. A design that presents this level of difficulty for university students would be even more challenging for K-12 students. This level of difficulty is one reason that more open hardware designs developed in universities are not replicated in K-12 schools.

Spring 2024

Based on this experience, the NTLS collaborators approached the OpenFlexure principal investigator, Richard Bowman, regarding possible collaboration on an adaptation of the OpenFlexure microscope designed for schools. He enthusiastically supported this effort. In the spring 2024 semester, undergraduate students enrolled in EDIS 2200 Design Through Making collaborated with Jo Watts, manager of the University of Virginia Make to Learn Laboratory, on development of an adaptation for schools.

The microscope on the right in Figure 2 is a medical-grade instrument that supports automated microscopy. It is designed for university research laboratories and medical centers. The microscope on the left is a version adapted for high school use. It is based on the same principles as the medical-grade microscope, but its functions have been adapted to facilitate simpler replication in school makerspaces.

Figure 2
An Educational Microscope (left) and a Research Microscope (right)



The research microscope incorporates three stepper motors that require a custom-designed motor controller. It is enclosed in a protective shroud, making its underlying functions and operation opaque.

In contrast, all of the components of the educational microscope are designed to be visible so that the function of each component can be easily understood. All of the electronic components are readily obtained from commercial sources. These adaptations make it accessible, affordable, and feasible for K-12 students to fabricate the design in a school makerspace. This version was published in the CAD Library (Watts & Bull, 2024)

Summer 2024

During summer 2024, a 6-week National Society for Black Engineers Pre-College Initiative Jr. Chapter (NSBE Jr.). Summer Engineering Academy was conducted for 15 students. Three of the NSBE Jr. students chose to participate in a microscope design workshop in the Make to Learn Laboratory at the University of Virginia. During this time, the high school students from Albemarle High School in Virginia were able to master the basic optical principles required to design a microscope. Working with their NSBE Jr. summer academy instructor, Albemarle High School biology teacher LaNika Barnes, the students successfully designed and fabricated a Lego-based microscope, using an open-source 3D-printed microscope as the inspiration for their design (Figure 3).

The NSBE Jr. Chapter at Albemarle County Public Schools (ACPS), in partnership with the NSBE Chapter at the University of Virginia, fosters leadership skills and offers STEM workshops and presentations for middle and high school students in addition to a Summer Academy. The chapter is open to all middle and high school students, regardless of their grade point average or socioeconomic background. Students must demonstrate an interest in STEM, and parents are encouraged to support the program and collaborate with other families. The students participating in the Make to Learn Laboratory during the summer engineering academy were not from a gifted program. Their academic performance was average. Some of them did not list college as an aspiration in a discussion of their career goals.

Figure 3
NSBE Jr. Students (on the right) Collaborate on Design of a Microscope

The students participating in the 6-week summer academy collected samples of plants and insects from their neighborhoods that they examined under a microscope. The students used these experiences and the example of a 3D-printed educational microscope in the CAD Library as the basis for designing their own microscope. They learned about the underlying principles of microscope design and developed an understanding of optical concepts such as the thin lens formula. They used everyday items found in their homes such as Legos, cardstock, and batteries (for construction of an illumination circuit) with which they had prior experience, and used these materials to develop a functional prototype microscope.

They also learned about trade-offs in microscope design. For example, they learned and observed firsthand that increased resolution may be obtained at the expense of decreased depth of field. They began by designing a single lens microscope and used that experience as the basis for a two-lens microscope. They then designed a focus mechanism that incorporated a worm gear, which introduced a new mechanical engineering concept to the students. In a fourth iteration, the students designed an illumination circuit that incorporated an LED, a battery, and a brightness control. In the process they learned about circuits and electrical engineering. During the course of the summer academy, the students learned that engineering design involves optimization of a set of variables to meet a design specification through an iterative process.

One of the female students mentioned “hair stylist” as a possible career. Other members of their families worked in this field providing role models for the students. Black women's hair is central to Black identity and culture. It is used to express personal style and identity and can have symbolic meaning that conveys messages about background. The students used a range of hair products and frequently bleached or changed their hair color. They noted that these changes had resulted in product buildup and caused damage to their hair.

Consequently, it was significant that one of the girls expressed interest in examining samples of her hair under the microscope. The students were able to see differences in the effects of different types of hair products on their hair that were visible under the microscope. One of the girls expressed interest in learning more about the underlying chemistry and rather than working as a hair stylist, working for a cosmetics company to design healthier hair care products.

In the process, the students may have begun to rethink their identity based on the capabilities that they developed. They were not only able to design and fabricate a microscope that will be modified and used by others but were also able to see a direct connection to their own lives. They also learned that an object that appears to be simple on the surface may be governed by complex design principles that can be challenging to understand. This result demonstrates that this type of hands-on learning experience can significantly impact underrepresented students’ sense of self-efficacy, interest, and perceptions of engineering careers (Denson, 2017).

Notably, all of the students continued to remain engaged when the school year began. Over the course of the fall semester, the engineering students have observed science students using the microscope in a biology unit. They have used their observations as the basis for continued discussion of ways to further enhance and refine the design. There were two key results of this pilot microscope design workshop implementation:

1. The engineering students were able to successfully design and fabricate a microscope in a summer academy with the support and scaffolding provided.

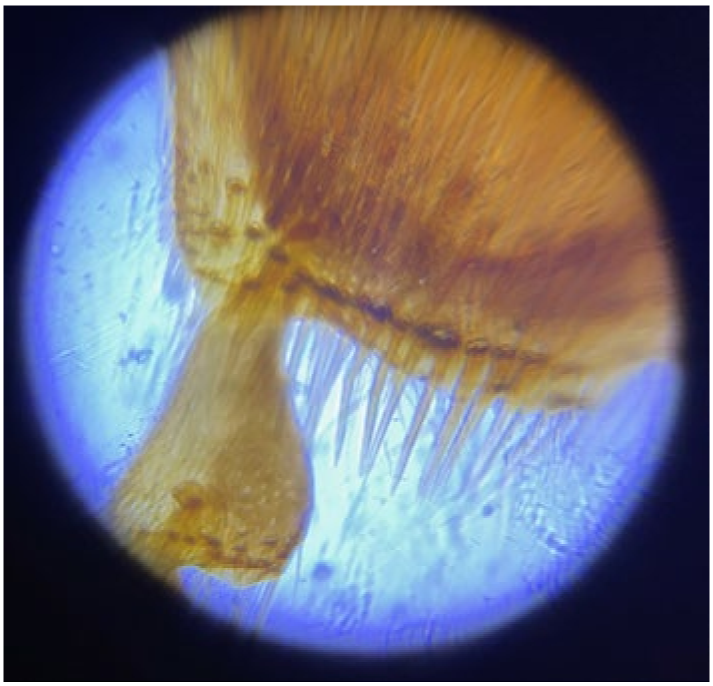
2. In the process, the teacher, LaNika Barnes, gained experience that has enabled her to continue working with the NSBE Jr. engineering students once the school year began.

The result demonstrated that in a small scale pilot, K-12 engineering students can design and fabricate microscopes that are subsequently used in science classrooms. This provided a context for discussion at the 2024 NTLS meeting.

NTLS 2024: K-12 Educational Microscopy

The work from the previous two summits served as a backdrop for the STEM strand at the NTLS in 2024. To anchor the strand, Barnes conducted a microscope workshop for participants in the strand. She provided an overview of pilot work that took place after NTLS 2023. To provide context, each of the participants assembled a microscope constructed from folded cardboard using a FoldScope Kit (www.FoldScope.com) designed at Stanford University. The participants were successful in capturing an image of a specimen on a slide using the camera on their cell phones (Figure 4).

Figure 4
Image of a Magnified Bee Wing Taken by an NTLS Participant



Barnes demonstrated the prototype microscope designed and fabricated by the NSBE Jr. engineering students. The NTLS participants had the opportunity to compare the images that they had obtained using their microscopes with the images that could be obtained through the student-designed microscope. The participants concluded that the experience of designing a microscope using a reference model in the CAD Library as a starting point for the design process is different from the experience of assembling a microscope from a kit.

Replicating Use of Open Hardware in Schools

Asim, a professor of science education at science at Indiana University Southeast noted that the majority of teacher education departments do not have engineering education programs. Consequently, teachers who graduate from these programs have few opportunities to receive formal training in engineering education and design. She explained that at her institution funds were more readily available for professional development in computer science than in engineering education. Therefore, both graduates of teacher education programs and the teacher education faculty members who prepare them often have little experience in engineering education.

This challenge is also reflected in significant disparities in opportunities to learn about both hardware manufacturing and software design. The National Academy of Sciences (2024) landmark study, *Equity in K-12 STEM Education*, highlighted this fact, noting, “The rapid growth of CS education … has been characterized with deep disparities in who has access to foundational computer science courses” (p. 11-14). In particular, high schools with high percentages of economically disadvantaged students are less likely to offer foundational computer science (Margolis et al., 2012; Margolis et al., 2015). Approximately 40% of open-hardware instruments at the university level involve use of a microprocessor (Heradio et al., 2018). Consequently, these projects also have a coding component, which is required for successful implementation of open hardware designs.

Two challenges are as follows:

1. How can these disparities in access to computer science and engineering education in K-12 schools be addressed?

2. How can teachers be prepared to support students in design and fabrication of open hardware designs in K-12 schools?

Islands of Excellence

The NSBE Jr. students presented their work at the Virginia Technology and Engineering Education Association (VTEEA) conference in August 2024. Geoffrey Estes, the career and technical education director for the Harrisonburg City Public Schools participated in this session. He reported that for more than 10 years engineering students in the Harrisonburg schools have participated in a program in which engineering teachers collaborated with science teachers to design open hardware instruments and apparatus for science instruction. Among other science tools, the engineering students fabricated an electrophoresis machine that is used for a DNA sequencing unit in biology classes.

As a result of longstanding disparities, the current situation might be described as islands of excellence in a broader sea of schools with fewer resources. Strategies used for implementation of open hardware design in university research laboratories provide a possible road map for a parallel in schools. Open hardware designs are often made available in public repositories with resources such as CAD files, a bill of materials, software files, and assembly instructions. For projects of any complexity, these files and resources rarely contain all of the information needed to successfully replicate the instrument at another site.

Online communities can provide needed assistance. Once an online community for a project reaches a certain size, there is generally someone in the community who can provide an answer to an issue or problem. For example, posts by the biomedical engineering students on the OpenFlexure forum generally received a helpful response within a few hours. It would not have been possible to replicate the design without this online support from the OpenFlexure community.

Building Online Communities of Distributed Expertise

Online communities play a critical role in the successful use of open hardware designs in universities. Online communities could potentially contribute to replication of open hardware designs in K-12 schools. It also suggests that a few open hardware designs that are supported by a large community may be preferable to many designs that each attract only a few users. A strategy for establishing a seed community of teachers with experience in implementing an engineering education program centered around a particular design is also required. One approach consists of collaborations between teachers and universities. The DNA sequencing machine developed by engineering students in the Harrisonburg schools was developed in collaboration with scientists at James Madison University. This indicates that that complex open hardware projects of this kind may be feasible through school-university collaborations.

Education associations also can play a potential role in this process. VTEEA, for example, provides ongoing professional development and support for teachers, both through in-person, hands-on workshops across Virginia and through online webinars. Consequently, once a few teachers implement an open hardware design with their students, they can share this experience with other educators. This is not a “train the trainer” strategy. Each teacher contributes expertise and experience to the process and typically adapts a process to local goals and conditions. Therefore, the term *shared distributed expertise* might be a better way to describe the strategy.

Considerations Regarding STEM Diversity

The specific example and prior NTLS pilot work anchored a broader discussion led by Robert Berry regarding STEM diversity. The specific work by NTLS participants is representative of a frequent theme in policy documents and discussions about diversity in the STEM fields, with the goal of greater involvement from diverse populations in STEM careers and STEM education. These discussions often mention the growing and changing needs of the American economy, the desire to maintain a technological edge over international competitors, and the necessity of safeguarding America from international security threats. A National Association of Manufacturers survey found that more than 67% of manufacturers cited attracting and retaining employees as their top challenge (Holland, 2024).

However, there is rarely any focus on the specific circumstances of the diverse populations and their communities, nor are there expansive discussions regarding the readiness of STEM fields for the increased diversity they desire. Positioning diverse populations for increased participation in STEM fields to meet interests that may not include their communities commodifies them by affixing a market value to their collective potential labor and intellectual property (Basile & Lopez, 2015).

With increased diversity, corporate executives and educators in STEM fields might expect ways of engaging, doing, and thinking to shift and change in the workplace and in workforce education. These shifts may reflect cultural aspects of diversity introduced into the field. Consequently, when considering teaching and learning, educators must center on cultural ways of engaging, doing, and thinking when working with learners. Educators should incorporate diverse cultures into teaching and learning rather than trying to integrate teaching and learning into diverse cultures.

Some questions that educators might consider with respect to STEM diversity include the following:

1. How are learning spaces and the broader STEM fields prepared to support diverse populations? What are the fields actively doing, or what have they actively done, to prepare for increased diversity?

2. What are the pathways for shifts and changes in learning spaces and STEM fields? STEM fields must consider that diversity opens pathways for previously unexplored questions, research, and thinking. Diversity allows for new and different questions.

3. How do we build the capacity to support STEM diversity and choice making? Diversity is an underexplored area for many spaces, and sustained dialog, engagement, and connections are necessary for developing a community.

The female NSBE Jr. students who worked with LaNika Barnes first became engaged when they found a connection to their own lives and experiences. This was a connection that the students made rather than one suggested by their instructor. This type of engagement cannot be scripted, but educators can be prepared to depart from a scheduled lesson to support and facilitate engagement when it occurs.

The Microscope Design Laboratory provides a mechanism to provide authentic learning experiences to students, engage them in ongoing observation and refinement of their design in action, and address school resource shortages: a win-win-win scenario. These types of STEM learning opportunities can also lead to students' development of a stronger STEM identity through

1. understanding of STEM subjects (i.e., competence),

2. active engagement with STEM concepts and materials, and

3. recognition by oneself and others as a STEM individual of belonging, capability, and purpose in engineering design and fabrication.

This was demonstrated through the engagement of the high school students in the microscope design and fabrication initiative. Even though they had no prior engineering experience, they voluntarily participated in the six-week design initiative. The results achieved may have resulted from the fact that participation was voluntary rather than mandatory. Consequently, the students began with a positive attitude and interest in the project.

Planning for a Prototype K-12 Microscopy Network

Kelly Dooley, the CEO and executive director ITEEA, led a planning session to explore next steps that build on prior work. A strategy to develop open hardware designs for schools and facilitate their use was identified:

1. Develop open hardware designs through collaborations between universities and K-12 schools.

2. After the pilot teachers gain experience with implementation of the open hardware designs in their schools, expand the network of teachers through workshops and professional development offered through state and national education associations.

3. Once the user community for a given open hardware design achieves a critical mass, expand use of the open hardware design through support and assistance provided by an online community of distributed expertise.

Development of a prototype K-12 Microscopy Network was identified as a method of exploring whether this approach might be viable. Cameron Denson, an associate professor of Technology, Engineering and Design Education at North Carolina, agreed to identify a rural school to serve as a third school, along with Albemarle High School and a Harrisonburg city school in Virginia to serve as the start of a Microscopy Network. Teachers in these three schools will use the CAD Library forum to share experiences in the same manner that the OpenFlexure forum is used to support fabrication of medical grade microscopes at the university level.

This work with a small-scale network consisting of three schools and two state engineering education associations will provide information about opportunities and challenges. This will inform development of a strategy to extend the prototype network to other schools.

If the strategy of employing distributed expertise across a small network of three schools and two universities is successful, ITEEA will collaborate with other NTLS associations and partners to make this type of experience available to teachers and students nationally. This can be achieved in partnership with ITEEA's network of consortium states, state affiliate associations, and Engineering by Design teachers. The goal is to build on the foundation of the previously established Educational CAD Model Library (www.CADLibrary.org), an educational manufacturing network that includes both teacher professional learning and peer support from other educators who have executed similar projects.

Publication of peer-reviewed open hardware models designed for K-12 schools is a necessary first step. However, this alone is not sufficient for the extension of open hardware designs to schools. Schools also need staff members who can fabricate the designs. K-12 engineering students who receive academic credit for fabricating designs offer one potential approach to addressing this issue. Schools also need access to engineering expertise. A distributed network of expertise offers a potential solution modeled on a strategy used by universities. The planned small-scale K-12 Microscope Network will provide an opportunity to explore the viability of this strategy.

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