

Establishing an Educational CAD Model Ecosystem

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During the past decade, many K-12 schools have established makerspaces with 3D printers, digital die cutters, and other fabrication tools. An open-source ecosystem is being developed to facilitate effective use of educational makerspaces. This work is being undertaken under the auspices of the National Technology Leadership Summit coalition, which includes national teacher educator associations in science education (ASTE), educational technology (SITE), engineering education (ITEEA), and mathematics education (AMTE), and the Fab Foundation – a network of more than 2,500 Fabrication Laboratories (Fab Labs). This effort is supported by a National Science Foundation Pathways to Open-Source Ecosystems Phase I planning grant (NSF No. 2229627).

The publication of Neil Gershenfeld's (2005) book, *Fab: The Coming Revolution on Your Desktop*, signaled the dawn of a new era in which affordable digital fabrication technologies would offer the equivalent of a "factory on a desktop." Makerspaces with fabrication technologies such as 3D printers were adopted in schools, libraries, and community centers, making affordable fabrication feasible in the same way that microcomputers made personal computing possible. Customized objects can now be fabricated in small quantities that previously would have required commercial production at a much larger scale to be economically feasible.

Our vision is for every K-12 student to have educationally effective hands-on learning experiences at every grade level. Students can learn concepts more deeply when they have the opportunity to engage in hands-on experimentation with physical objects, such as mathematical manipulatives in mathematics education, experimental apparatus in science education, and physical gear trains in engineering projects. To realize this vision, we are collectively developing an ecosystem to support effective use of *educational objects* in schools. This report describes the current status of this work and future plans.

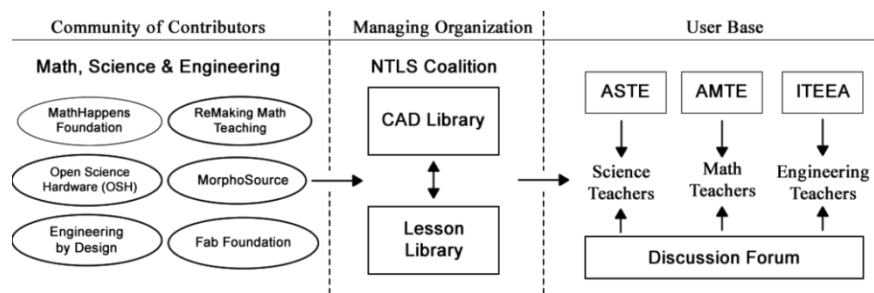
The educational effectiveness of tools in K-12 makerspaces requires access to useful computer-assisted design (CAD) models and associated instructional supports for teachers. The goal of the current National Science Foundation (NSF) Pathways to Open-Source Ecosystems (POSE) Phase I initiative is to establish an ecosystem for open-source educational models and associated instruction supports. The planning and development process consists of four major components:

1. A sustainable organizational structure to manage a library of educational objects and associated elements of the ecosystem.
2. The technical infrastructure for a CAD Library of curated, peer-reviewed educational models designed to address K-12 instructional objectives.
3. A community of external developers who contribute objects and associated instructional materials to the library.
4. A community of users who have the support needed to use the objects to address K-12 educational objectives.

Organizational Structure of the Ecosystem

An overview of these components is depicted in Figure 1. The National Technology Leadership Summit (NTLS) coalition provides the framework for managing the components. The NTLS was established in 1999 with seed support from the U.S. Department of Education. This initiative brought together the presidents and leaders of 12 national teacher education associations with the goal of collaborating across disciplinary lines.

Figure 1
Contributors, Managing Organization, and Users



The NTLs coalition includes national teacher educator associations in the four STEM content areas of science education (Association for Science Teacher Education, ASTE), educational technology (Society for Information Technology and Teacher Education, SITE), engineering education (*International Technology and Engineering Educators Association*, ITEEA), and mathematics education (Association of Mathematics Teacher Educators, AMTE) as well as associations representing the humanities. Each year the presidents and leaders of the NTLs coalition meet for an annual invitational technology leadership summit in Washington, DC. This is the only time that presidents of the associations meet face-to-face to plan and coordinate collective efforts. All 12 charter members have continued to participate in NTLs for 25 years, demonstrating that it is a stable, mature organization capable of sustaining the planned extension of its current activities. These activities include review and publication of educational objects, collaboration and coordination of efforts with external developers, provision of support and training users through workshops at teacher-focused conferences, and articles in teacher-focused journals.

CAD Library

A curated, peer-reviewed library of educational objects is the core of the ecosystem serving as a central hub that connects external contributors, reviewers, and users. The open-source Educational CAD Model Library (CAD Library) has two components:

1. Technical Infrastructure
2. A Process for Reviewing and Publishing Objects

Technical Infrastructure

The repository of objects being transitioned had been housed in GitHub for convenience. However, GitHub was designed for technical users rather than teachers. For that reason, a repository designed specifically for scholarly objects is being developed to house the CAD Library. The Dataverse is open-source database software developed by the Institute for Quantitative Social Science at Harvard University. Objects in the CAD

Library are housed in an instance of the Dataverse managed by the University of Virginia Library. The University of Virginia (UVA) was an early developer of digital scholarship in the 1990s, establishing an Electronic Text Center, a Digital History Center, a Geographic Information Services Center, and the Institute for Advanced Technology in the Humanities, and more. One of the leaders in this effort, John Unsworth, is now UVA's dean of libraries and university librarian.

This leadership and longstanding experience will ensure that the capacity to build and maintain the technical infrastructure is sustainable. The University's repository librarian provides leadership and oversight of the Dataverse, including the CAD Library. There are a number of advantages that accrue to the use of the Dataverse software to house objects in the CAD Library.

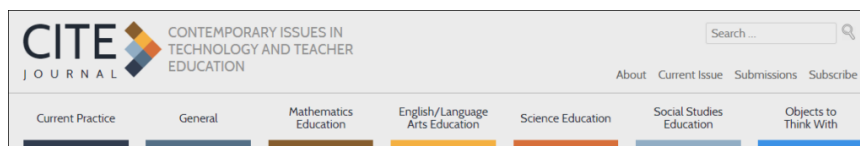
1. There is no charge for storage of data in the UVA Dataverse; the University maintains it.
2. The University will maintain it in perpetuity (i.e., as long as there is a UVA library).
3. Each item published in the repository is assigned a Document Object Identifier (DOI).
4. There is an application interface (API) that can be used to add objects to the repository and retrieve them.

The API is used to retrieve objects and associated information from the back-end database (i.e., the Dataverse) and display them in a user-friendly format. The web address "CADLibrary.org" has been secured for the CAD Library.

Reviewing and Publishing Objects

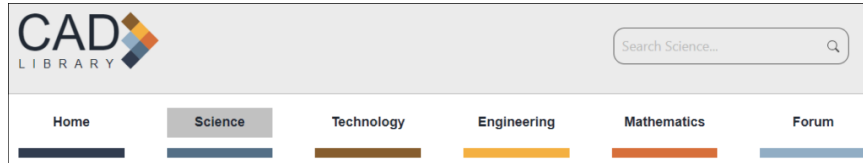
The NTLs coalition has a long history of peer reviewing works for practicing teachers. Among other joint initiatives, the NTLs coalition has published an open-source peer-reviewed journal, the *Contemporary Issues in Technology and Teacher Education (CITE Journal, www.citejournal.org)*, for 25 years. Each association selects the editors and manages the review process for the discipline for which it has responsibility. The science section is managed by ASTE and the mathematics section is managed by AMTE. To advance the POSE initiative, a new section for engineering, Objects to Think With, sponsored by the ITEEA was added to the journal.

Figure 2
Masthead of the CITE Journal



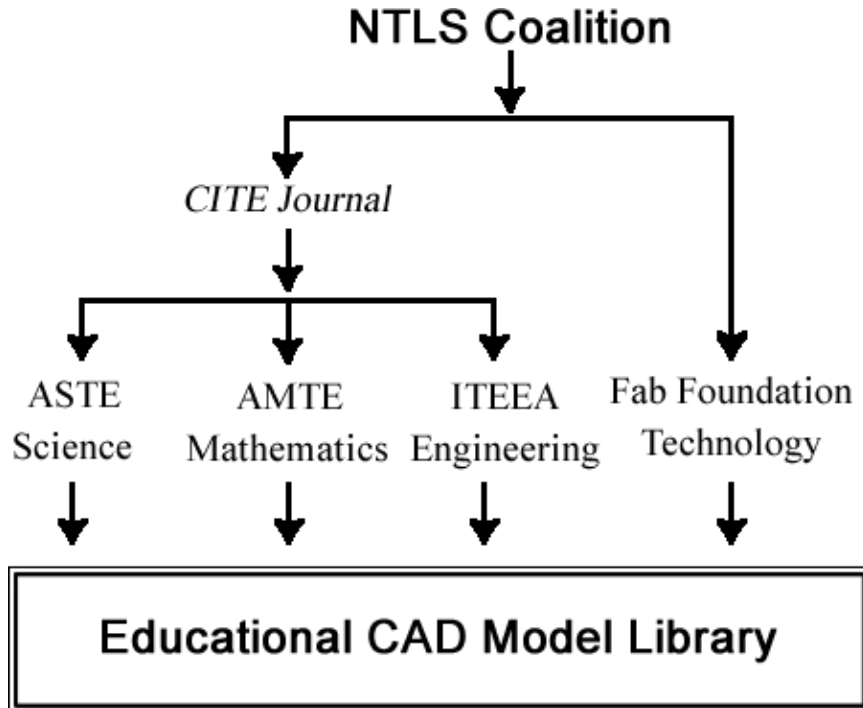
The CAD Library is being developed as an extension of the *CITE Journal*. Both the *CITE Journal* and the CAD Library are sponsored by the NTLs Coalition (<https://ntls.info>) and affiliated professional associations. By design, the masthead of the CAD Library (Figure 3) mirrors the masthead of the *CITE Journal*. In the same way that the journal is a repository of peer-reviewed manuscripts, the CAD Library is a repository of peer-reviewed educational objects.

Figure 3
CAD Library Masthead



A Curators' Council for the CAD Library extends the *CITE Journal* organizational model. Like the editors of the *CITE Journal*, the curators for each collection (science, technology, engineering, mathematics, etc.) have autonomy over their individual collections (Figure 4).

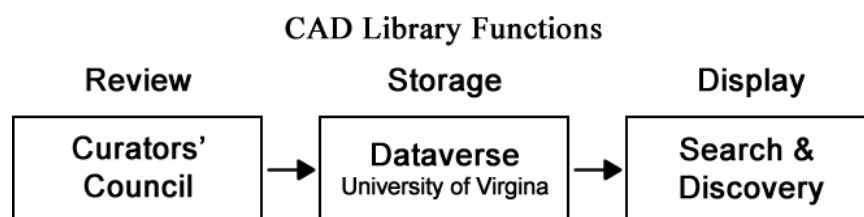
Figure 4
Organizational Structure for Management of the CAD Library



The initial curators of the science and engineering sections of the CAD Library are the editors of the science and engineering sections of the *CITE Journal*. The curator of the mathematics section of the CAD Library is working closely with the editor of the mathematics section of the *CITE Journal*. The close working relationship between the respective boards of the *CITE Journal* and the CAD Library will facilitate extension of the review process to include educational objects as well as manuscripts.

The management functions associated with the CAD Library include review of submitted educational objects, storage of educational objects and associated data that have been accepted for publication, and discovery and display of objects (Figure 5).

Figure 5
Functions of the CAD Library




The editors of the *CITE Journal* will encourage authors of educational objects to copublish articles describing their use in the journal. The CAD Library curators work closely with the *CITE Journal* editors to facilitate this process. This serves two purposes. First, it provides additional context about the educational use of objects published in the CAD Library. Second, peer-reviewed publication serves as an incentive to encourage faculty members to collaborate with teachers on the development of educational objects. These joint collaborations between teacher education faculty and teachers professionalize the experience for both constituents.

Search and Discovery

A vibrant ecosystem of model creation and use in K-12 education requires the means to make effective (in the pedagogy of the classroom) educational objects discoverable by teachers who have little time to investigate the details of numerous objects to find one suitable to the intent of their instruction. One of the more important initial tasks of the CAD Library Curators' Council consisted of the development of descriptive metadata fields associated with each object. The metadata fields associated with objects include terms that can be recognized and understood by teachers, such as discipline (science, mathematics, etc.), subdiscipline (algebra, geometry, etc.), grade level, and instructional standards. Use of common agreed-upon metadata fields will facilitate searches across objects developed by many different organizations (Figure 6).

Figure 6
Displaying an Object Identified Through the CAD Library Search Function

Fraction Orange



The Fraction Orange is a sphere partitioned into two hemispheres; one hemisphere is further partitioned into fourths, eighths, and sixteenths of the whole; the other hemisphere is further partitioned into sixths and eighteenths.

Big Idea
The Fraction Orange manipulative is a particularly useful tool for exploring the measurement meaning of division. It's also useful for teaching fractions through multiple representations, like drawings of partitioned wholes and symbols of the form a/b .

Developer
[ReMaking Teaching](#)

Subject
Mathematics

Grade Levels
1, 2, 3

Download

- [Instructional Resources](#)
- [Fabrication Guide](#)

[Discuss](#)

Sample Learning Goals

- Interpret a fraction as division.
- Interpret a fraction a/b (with $a > 1$) as a sum of fractions $1/b$.
- Interpret and compute quotients of fractions, and solve word problems involving division of fractions by fractions.
- Explain why one fraction is equivalent to another using a physical fraction model, even though the numbers and sizes of their parts differ.

Citation
Pomponio, E. (2023). *Fraction Orange* [Educational Object]. *Educational CAD Model Library*. Published March 24, 2023. NTLS Coalition. doi:10.18130/V3/JDRILP

The agreed-upon metadata fields are being incorporated as a new block in the UVA instance of the Dataverse that houses objects in the CAD Library. One of the responsibilities of curators is to work with authors to ensure that metadata fields are appropriate and complete prior to publication of an object.

Citation of Objects in the CAD Library

Academic journals play a key role in knowledge generation and dissemination. In *The Scientific Journal* (2018), Alex Csiszar noted, “The value ascribed to publishing research papers ... influences the kinds of projects researchers choose to pursue, and the modes of collaboration in which they routinely engage ...” (p. 2). In the same way that journals serve as engines to generate, validate, and disseminate scientific knowledge, *a peer-reviewed CAD Library will serve as an engine to generate, validate, and disseminate educational objects.*

Citation is a crucial element of knowledge generation and dissemination. The CAD Library Curators’ Council have collectively agreed upon the following citation format for educational objects:

Pomponio, E. (2023). *Fraction Orange* [Educational Object]. *Educational CAD Model Library*. Published April 27, 2023. NTLS Coalition. doi:10.18130/V3/JDRILP

The NTLS Coalition serves as the publisher, providing assurance that educational objects in the CAD Library have undergone a peer-review process prior to publication.

External Developers

Communities of external developers have been identified who are actively developing educational objects for the areas of mathematics, science, and engineering. Each of the organizations or communities listed in Table 1 have agreed to collaborate on submission of previously developed objects in existing repositories to the CAD Library for publication and review. This will seed the CAD Library with examples of educationally effective objects. These examples are only illustrative of many other organizations as well as teachers who are actively developing educational objects.

Table 1
Examples of Selected Development Communities and Related User Communities in Science, Mathematics and Engineering

Content	Contributors	User Communities
Science	MorphoSource Open Science Hardware	ASTE Science Teachers
Mathematics	Math Happens Foundation ReMaking Mathematics	AMTE Mathematics Teachers
Engineering	Engineering by Design Fabrication Laboratories	IITEEA Engineering Teachers

Currently, these objects are disbursed across many web sites. A process to identify and review these objects, attaching common metadata fields in the process, will facilitate discovery and use. A more detailed description of each of these external developers is provided in the following section. The user communities and associated professional associations (ASTE, AMTE, and IITEEA) are described in more detail in the section on user communities. Descriptions of external developers and contributors in the areas of science, mathematics, and engineering are provided in this section.

Science Developers

Morphosource

MorphoSource is a repository of 3D data developed with NSF support (NSF Grant Nos. 1661386 and 2149257) representing the world's natural history, cultural heritage, and scientific collections contributed by the curators of science museums, researchers, and scholars. The collection of more than 70,000 objects is designed to share findings, increase impact, and improve access to material critical for scientific discovery. More than a thousand teachers currently use these models.

A survey of teachers regarding the models that are used most often found that addition of lesson plans and associated instructional support materials increases use of models in schools. Inclusion of the models that

are most used in K-12 teaching in the Educational CAD Model Library offers several benefits. It will increase discoverability through a user interface specifically designed for teachers. It will also provide collaborative opportunities for development of lessons to accompany MorphoSource models and for the remixing of those models. It will provide teachers using these materials with opportunities to discover similar materials from other scientific collections.

Open Science Hardware

An open science hardware movement has grown exponentially in universities and colleges in recent years. This movement has been fueled by digital fabrication technologies and inexpensive microcontrollers. The Gathering for Open Science Hardware was established in 2016 to provide a roadmap for development of open science hardware. This organization describes open science hardware as “science hardware that is open source – or free to use, change, study or distribute” (<https://openhardware.science/>); in other words, it is the hardware counterpart of open-source software.

The OpenFlexure microscope, for example, is a laboratory-grade microscope that can be constructed using 3D printed parts and a Raspberry Pi single-board computer. The cost for an OpenFlexure microscope is a few hundred dollars, whereas the commercial equivalent may cost thousands. The principal investigators of open science hardware products developed with NSF support have an opportunity to broaden their outreach through adaptation of these products for K-12 use through submission to the CAD Library.

Mathematics Developers

MathHappens Foundation

The MathHappens Foundation was established in 2014 to provide teachers with exemplary hands-on mathematics materials. During the last decade, the foundation has developed an extensive library of mathematical objects and associated instructional materials that are widely used by K-12 teachers. Inclusion of the MathHappens materials and models in the CAD Library will make these materials available to a larger audience of teachers. In addition, combining mathematics materials from the MathHappens website with similar materials from other websites ensures that mathematics teachers can access mathematical models from multiple sources through a common search mechanism.

ReMaking Mathematics

The ReMaking Mathematics initiative was established with support from an NSF grant (No. 1660719). In this project, preservice teachers receive mentorship for development of mathematical manipulatives used in teaching. Existing mathematical models developed through this NSF program will be submitted to the CAD Library for review and publication. In addition, this program can potentially be extended to other teacher education programs with makerspaces.

Engineering Developers

TeachEngineering

The TeachEngineering Digital Library was founded in 2001 and is funded by NSF grants (Nos. 0226322 and 1544495). It features peer-reviewed, classroom-tested curricular resources aligned to various STEM educational standards that include state science and math, *Next Generation Science Standards* and *Common Core State Standards for Mathematics*. This includes more than 1,800 science, mathematics, and engineering lessons and activities. Most curricular contributions are authored by the teachers, professors, and graduate students associated with NSF-funded engineering colleges from across the country, primarily GK-12 and Research Experience for Teachers grantees.

The CAD Library enables CAD Models and other educational objects featured in TeachEngineering to be easily accessed and downloaded by teachers. In addition, TeachEngineering can leverage over 20 years of experience producing STEM lessons to help teachers who have contributed educational objects to the CAD Library develop accompanying lessons that can also be featured in the TeachEngineering Library. This will increase the range and diversity of teachers who are using both TeachEngineering and the CAD Library.

Fab Foundation

The Fab Foundation was established in 2009 to support an international network of more than 2,500 Fabrication Laboratories (Fab Labs). The Fab Foundation is a nonprofit foundation that emerged from the Massachusetts Institute of Technology's Center for Bits and Atoms Fab Lab program. Its mission is to enable anyone to make (almost) anything using technology and digital fabrication. They are currently sponsoring the Fab Learning Academy, which enables teachers to use Fab Lab resources to design and make educational objects that support hands-on learning. Exemplary lessons are housed in an associated library of community-contributed lessons that utilize digital fabrication.

The Fab Foundation has more than 7 years of experience with crowd-sourced lessons. Educational objects produced by teachers in Fab Learning Academies that are identified as exemplary by the Fab Foundation will be submitted to the appropriate CAD Library curator for review. In this way, the Lesson Library will serve as a crowd-sourced incubator designed to identify exemplary teacher-made and student-made educational objects. In addition, when educational objects are accepted for publication in the CAD Library, linked lesson plans and other instructional resources associated with these objects will be published in the Lesson Library.

User Communities

The three major user communities consist of K-12 teachers and students addressing topics in science, mathematics, and engineering through the use of hands-on learning. The licensure and accreditation procedures and

instructional objectives for all three areas are different. However, many of the objects used to teach science (for example) also have mathematics and engineering components that can be used to address topics in those areas. This presents opportunities for collaboration.

Each of the three communities is anchored by the corresponding teacher educator association: ITEEA for engineering education, ASTE for science education, and AMTE for mathematics education. For 25 years these three associations have been collaborating with one another on common projects through the framework of the NTLs Coalition. This prior collaborative relationship will facilitate coordination of joint efforts related to establishment of an ecosystem around the CAD Library.

In addition to the user communities served by these associations, each of the external developers described in the preceding section also brings its own user base to the table through collaboration in this effort.

Professional Associations

All of the participating educational associations have a broad array of professional development offerings for members. These include hands-on workshops at conferences, webinars, podcasts, and a variety of other opportunities.

Engineering Community – ITEEA

The ITEEA has a membership of more than 5,000 technology and engineering education teachers. These teachers use the ITEEA Engineering by Design curriculum in their instruction. Consequently, integration of lessons and instructional materials associated with objects in the CAD Library has the potential to reach a substantial audience of K-12 teachers. Each of these teachers instructs more than 100 students each year. Thus, a tight coupling between the CAD Library and the Engineering by Design curriculum has the potential to reach and serve a large audience. (Note: By prior agreement with ITEEA as a condition of this initiative, all materials in the CAD Library will be made freely available to both ITEEA members and nonmembers. Consequently, the potential community of teachers who may be reached is even greater.)

The process of integrating objects in the CAD Library with the Engineering by Design Curriculum was piloted with an Animation Machine. In the laboratory accompanying this object, students create animation using a computer simulation, construct basic physical animation machines, research the history of animation machines, and design and build an animation machine of their own. Ryan Novitski, the ITEEA director of STEM learning, collaborated with K-12 engineering teachers to adapt this sequence for use as a module in the Engineering by Design curriculum. The unit was then piloted by the ITEEA president in a middle school engineering class in Suffolk, Virginia. She then used the experience gained as the basis for a one-day preconference workshop for other middle school engineering teachers at the Virginia Technology and Engineering Education Association annual conference. This pilot implementation will now be used as the basis for a similar workshop at the ITEEA national

conference and will be made available nationally as a module in the Engineering by Design curriculum.

In addition to the user base and community provided through ITEEA, the Fab Foundation will also make this module and similar objects in the CAD Library available to teachers collaborating with its network of 2,500 fabrication laboratories. This work will be supported through the Fab Learning Academy.

Science Education Community – ASTE

ASTE has a membership of more than 1,000 teacher educators who prepare future science teachers in schools and colleges of education. In addition, many of these science education professors work directly with in-service teachers in their local service area. Consequently, the value for ASTE is that the objects and materials in the CAD Library can be used to support both preservice and in-service teacher education for laboratories and science demonstrations that involve hands-on learning.

The president of ASTE has piloted this process by participating in development of science education materials for the CAD Library, piloting the unit with a middle school teacher. The resulting unit will be presented at the national ASTE conference in January 2024. As the curators of the Science Education section of the CAD Library conduct workshops at science education conferences, they can begin to support other science education faculty members who are introducing this resource in their teacher education programs.

Mathematics Education Community – AMTE

Mathematics teachers have traditionally incorporated physical and digital mathematics manipulatives into their teaching. AMTE has a membership of more than 1,000 teacher educators who prepare future mathematics teachers in schools of education. The value for AMTE parallels that for ASTE in science education; that is, the objects and materials in the CAD Library can be used to support both preservice and in-service teacher education for mathematics instruction that involves hands-on learning.

A prior NSF initiative, ReMaking Mathematics, focused on use of makerspaces to extend the range of physical manipulatives available to mathematics teachers. Workshops at regional and national conferences attended by mathematics teachers introduced them to these resources. Integration of these objects and resources, currently housed in a different location, will introduce this community of users to resources in the CAD Library.

Community Forum

An associated forum (forum.CADLibrary.org) will provide a site for discussion of educational objects and lesson plans. This forum was established using an open-source application, Discourse. The forum was implemented with consultation and input from Michael K. Johnson, who previously provided leadership for the establishment of one of the most

significant open-source ecosystems, serving as the founding Fedora Project Leader. Fedora is an open-source Linux distribution that currently has more than 1.6 million users, with a thriving community of discourse and associated ecosystem built around it. A core principle is that “communications should meet people's social needs as well as foster communication that is clearly intrinsic to progress.” (Personal communication, Johnson, M.K.)

Anticipated uses of the forum include the following:

1. Facilitation and Support - Manuals and user guides cover only a fraction of the knowledge required for projects of any complexity. The forum community serves as a collective intelligence for facilitation and support for provision of answers that otherwise may have been unobtainable.
2. Collaboration on a Project - Teachers working on a novel project often benefit by sharing the project for feedback at various stages of development. This often leads to enhancements that improve the final result.
3. Sharing and Validation - Makers enjoy sharing projects in a form that others can replicate. The process of sharing often results in positive validation and feedback.
4. Archive of Identified Solutions - The forum also can serve as a repository of solutions to commonly recurring issues.

The CAD Library forum is currently under development. When completed, each object in the CAD Library will include an option to create a strand on the forum if one does not exist. (If a forum strand already exists for that object, a link will take the user to that strand.)

A survey of journal articles describing open hardware projects found that 40% of these projects involved the use of microcontrollers (Heradio et al., 2018). Therefore, it is desirable to make connections to communities of users who are incorporating microcontrollers in projects in informal and formal learning at the K-12 level. The educational programming language Scratch is currently the 12th-most-used computing language (educational or professional) according to the TIOBE index (<https://www.tiobe.com/tiobe-index/>). The lead developer for the initial implementation of Scratch, John Maloney, has now developed an educational language for microcontrollers inspired by Scratch.

MicroBlocks enables students who are familiar with the Scratch programming interface and conventions to extend this expertise to use of microcontrollers in physical computing projects. In 2 years, the number of weekly users employing MicroBlocks for physical computing projects involving Chromebooks has grown from 2,000 weekly users to 10,000 weekly users. (The distribution between informal and formal education is not known.) The community forum for the CAD Library will also be used as a forum for MicroBlocks. This will ensure that this growing community of users engaged in physical computing projects have opportunities to discover open-source hardware projects in the CAD Library.

Collaboration Across the Organizations and Disciplines

In addition to the potential user base in each of these three areas, the CAD Library can potentially serve as a catalyst to spark collaboration across organizations and disciplines. This example is based on an educational object that was developed in spring and summer 2023. Development of this object is still in midprocess, so the latter part of the description describes plans that will be implemented in fall 2023. Most educational objects will not involve collaborations that are this extensive, but it is presented as an example of the potential for collaboration through the CAD Library.

Facilitating Development of a Teacher-Designed Object – Fab Learning Academy

Fab Learning Academy is a distributed education program designed to introduce teachers to digital fabrication tools and their pedagogical use in the classroom for K-12 content learning. The open-source wave machine illustrated in Figure 7 is one of the objects developed by an educator in Singapore participating in the pilot implementation of the Fab Learning Academy in spring 2023.

Figure 7
Teacher-Designed Object Developed Through the Fab Learning Academy



This object consists of a series of cams that raise and lower a series of rods to illustrate wave motion as a crank is turned. There are a number of similar mechanisms, some commercial and some open source, that have been previously developed to illustrate wave motion. This version was developed to help K-12 students explore waves in our environment and

related characteristics of sinusoidal waves—amplitude, frequency, and wavelength.

Replicating the Educational Object at Another Site – Make to Learn Laboratory

The CAD files for this machine were used to replicate the wave machine in the Make to Learn Laboratory at the University of Virginia. Enhancements included the development of a supplementary model consisting of a single cam and rod to enable students to isolate a single cycle (Figure 8).

Figure 8
Isolated Rod-and-Cam Section of Wave Machine



Other enhancements included the addition of calibration marks to enable students to relate the phase of the cycle in degrees to the height of the rod in millimeters. Addition of calibration marks made it possible to develop a table in which students recorded data for one rotation of the cam and subsequently used the data to construct a graph of a sine wave. This exercise complemented existing lessons that have been created digitally by teachers using open-source tools such as GeoGebra.

Reviewing and Refining Related Instructional Materials - Science Education

The president of ASTE, Andrea Borowczak, identified a science educator to work with a pilot teacher to ensure that the instructional materials and supports provided can be effectively used. The teacher educator, Sumreen Asim, is an associate professor of science and technology education at

Indiana University Southeast. Her research focus is elementary and middle school science.

Identifying a Teacher to Pilot Use of the Object in a Classroom – Hawaii STEM Academy

A member of the board of SITE identified a STEM Academy serving 750 middle school teachers across 80 middle schools in Hawaii. The director of the STEM Academy, Cheryl Sato Ishii, confirmed that topics that could be addressed through use of the wave machine, such as wave motion, frequency, amplitude, phase, and wave length, were aligned with the middle school science objectives.

Fabricating a Local Copy - Engineering Education

To successfully implement the pilot use of the object in a classroom, the revised wave machine will need to be replicated locally. The individual who fabricates and assembles the object for the teacher is not necessarily the teacher who will be using it. The ITEEA is in the process of revising its Engineering by Design curriculum to enable advanced K-12 engineering students to receive credit for collaboration with a teacher on fabrication of an object. (Research suggests that greater depth of learning can be achieved for educational activities that involve an authentic purpose or use such as this.)

The ITEEA director of STEM learning, Ryan Novitski, is in the process of identifying a STEM educator in Hawaii who can supervise local replication of the wave machine by a student in a technology and engineering education class. Local replication makes it easier to directly observe and address any issues that may arise in use of the wave machine. If the pilot implementation is successful and can be scaled, ITEEA may eventually incorporate this module in its Engineering by Design curriculum, making it available to the more than 5,000 K-12 engineering and technology teachers who use this curriculum.

Publishing the Object in the CAD Library

When an object is published in the CAD Library, it is assigned a DOI that is used as a permanent reference for subsequent uses. The DOI, in turn, can tie together collaboration and use across all of the organizations, entities, and schools in the open-source ecosystem. In addition, an open-source discussion tool, Discourse, has been established to facilitate collaborative discussions related to an object. This will enable teachers who have questions, need consultation, or who wish to describe innovative teaching uses have access to a support community to facilitate use.

Publishing a Related Peer-Reviewed Lesson – TeachEngineering

Once the pilot classroom implementation is completed and documented, and the object is published in the CAD Library, the associated description of the classroom activity may also be added to the lessons published by

TeachEngineering. TeachEngineering was founded in 2001 and is funded by the National Science Foundation. It features peer-reviewed curricular materials aligned with the *Next-Generation Science Standards*. This includes more than 1,500 science, mathematics, and engineering lessons. Staff members that include engineers and educators work with teachers to ensure that the final lessons published are educationally effective. The same rubrics used to review other lessons in the TeachEngineering library will also be applied to lessons accompanying objects in the CAD Library.

Developing Consensus on Standards for Reviewing Objects

The participating associations that are managing the CAD Library will need to develop and agree upon standards for reviewing objects. The current process for reviewing objects published in the CAD Library involves two requirements that go beyond the review process for reviewing academic manuscripts:

1. The object must be replicated by someone other than the original designer. CAD models in existing repositories that have not undergone peer review, such as Thingiverse, often present issues when teachers attempt to replicate these objects. Files may not print properly, or assembly directions may be unclear. Replication and review prior to publication is designed to identify fabrication issues and address them prior to making the objects available to teachers.
2. The object must be used by at least one teacher other than the developer (in the case of teacher-designed objects) to successfully address an educational objective. This component of the review process is designed to ensure that adequate instructional supports are available to enable other teachers to use the object successfully. The description of classroom implementation will be included in resources made available when the object is published.

The review process described in the example of the wave machine in the preceding example involved the following steps:

1. Facilitating development of a teacher-designed object.
2. Replicating the educational object at another site.
3. Reviewing and refining related instructional materials.
4. Identifying a teacher to replicate the instruction in another classroom.
5. Fabricating and refining a copy of the object for the teacher at a local site.
6. Publishing the reviewed object in the CAD Library.
7. Publishing a related peer-reviewed lesson that accompanies the object.

Any of the organizations described here could have assumed any of the roles described. For example, in the illustration, the Fab Learning Academy facilitated development of a teacher-made object while the peer-reviewed lesson was facilitated and published by TeachEngineering. However, the example could as easily have described

ways in which an object such as a cube in a lesson about fractions in the Teach Learning lesson library was developed and published in the CAD Library with links back to the original lesson.

The roles and sequence of steps in the development and review process prior to publication in the CAD Library are not prescriptive or definitive. Rather, they are intended to stimulate conversations among partners in an emerging ecosystem designed to encourage and facilitate use of open-source objects in schools as well as colleges and universities.

Next Steps

The process of reviewing, implementing, documenting, and publishing the educational object described in the example is still in progress. We will almost certainly learn a great deal as we move through a complete cycle of replication, classroom implementation, and publication in the CAD Library. This illustration is designed to anchor a discussion of ways in which long-established institutions such as the Fab Foundation, TeachEngineering, a science education association (ASTE), an engineering education association (ITEEA), a mathematics education association (AMTE), an instructional technology association (SITE), and others can collaborate within a common framework and ecosystem established by the NTLS coalition.

The CAD Library and its potential to extend use of open hardware is a major focus of the National Technology Leadership Summit in fall 2023. The CAD Library curators, association presidents, and journal editors have further opportunities to discuss directions and next steps in person at that venue.

There are still a number of steps that need to be taken to fully realize the potential of the CAD Library as a catalyst for developing an ecosystem around open-source educational objects employed for hands-on learning in schools. These steps include:

Continued Development of Technical Infrastructure

A great deal of progress has been made in the development of the technical infrastructure to support the CAD Library. The UVA instance of the Dataverse has been modified to incorporate a new metadata block with the metadata fields agreed upon by the Curators' Council. Basic search and display functionality has been added. However, there are still a number of features that need to be completed. Associations need to agree upon the instructional standards that will be employed in the corresponding metadata fields. The process for linking objects in the *CAD Library* to corresponding threads in the community forum needs to be implemented. Procedures for adding new teachers to the discussion forum and moderating posts on the forum need to be established. Other enhancements and improvements to the technical infrastructure will be made during the current soft opening phase when a test set of objects is being used by a small subset of pilot users.

Continued Development of Review Processes

The respective curators will need to develop review boards for each content area and continue to refine the process for reviewing and publishing educational objects.

Collaboration With External Developers

The processes for collaborating with external developers and supporting them need to be refined. Each external developer (and its associated community) has different needs and requirements. Processes for ensuring that the voices of these crucial stakeholders and contributors are incorporated into the planning process will be important.

Development of the User Base of Teachers

Organizations such as MorphoSource (in science education) and TeachEngineering (in engineering education) have years of NSF-supported experience in developing and serving a user base of teachers. The one consistent message is that it is an ongoing process that requires a great deal of ongoing support and effort. This will include development of a program of workshops at teacher-focused conferences such as the annual meetings of the National Council of Teachers of Mathematics, the National Science Teacher Association, and the International Technology and Engineering Education Association, and related regional and state conferences organized by these groups. Leaders from each community will also need to author and publish related articles in teacher-focused journals such as the *Mathematics Teacher*, the *Science Teacher*, and the *Technology and Engineering Teacher*. These efforts and other methods such as webinars will be used to introduce teachers to resources in the CAD Library and support them in use of educational objects for hands-on learning as part of an ongoing effort.

Parallel efforts will take place at the preservice teacher education level. AMTE and ASTE are professional associations for the teacher education faculty at universities who prepare teachers. Therefore, incorporating use of objects in the CAD Library in teacher preparation has the potential to reach substantial numbers of teachers over time.

Development of Methods for Evaluating Progress and Sustainability

Once the fully functioning CAD Library is launched – a milestone currently planned to coincide with the 2023 National Technology Leadership Summit in fall 2023 – methods for evaluating progress and sustainability will be needed. These metrics will need to monitor both the success in encouraging submission and publication of objects in each STEM area, but also the extent to which the resource is being adopted and used by science, mathematics, and engineering teachers.

Summary

This planning document, updated on an ongoing basis, has served as a method for building consensus and agreement about joint directions across associations. This version is being published in the *CITE Journal* as a way of disseminating information about this effort to the respective members of each participating association and other stakeholders. The document will be periodically updated to reflect the current status of the project.

One of the key characteristics that distinguishes an individual NSF project from an ecosystem is a distributed management structure that spans multiple development communities and a user base that transcends any individual project. A key marker of a sustainable ecosystem is one in which there is an effective transition of leadership from one generation of leaders to the next. During the quarter century in which the educational associations participating in the NTLs Coalition have collaborated with one another across educational disciplines, there have been multiple successful transitions in leadership, as the founders have been succeeded by new generations.

The CAD Library will aggregate educational objects developed through more than a dozen NSF grants administered by a half-dozen different organizations. The participating educational associations are ideally suited to successfully develop and support the new functionality that will be provided by the CAD Library. The CAD Library builds upon a successful model of peer-reviewed journals published by the NTLs Coalition. The same infrastructure that supports the manuscript review process can be extended to encompass educational objects as well.

The presidents of the associations participating in NTLs also have extensive backgrounds with respect to organization and leadership in their respective disciplines. The backgrounds of each of these association presidents is available on their respective associations' web pages. These organizations have a long history of collaboration through NTLs. This experience with a variety of leadership roles and governance structures positions the group to establish a successful management structure for the current effort.

One of the key roles of these organizations is provision of professional development and education for association members. The associations represented include the teacher educator associations for all of the STEM disciplines. Attrition in the teaching profession results in replacement of one-half of all teachers during the course of a 5-year period. Therefore, integration of effective use of the CAD Library in teacher education program coursework can result in a high percentage of use by new teachers as they graduate and enter the teaching profession. This method has been successfully used to integrate prior technologies such as graphing calculators and web-based simulations in teaching. The same approach can now be extended to the use of educational objects in teaching.

In order for fields of knowledge to advance, they must be organized in a systematic way. The peer-reviewed journal system provides a means of

doing this for academic manuscripts. The proposed system for review and publication of educational objects will play a similar role in identifying educationally effective objects. An agreed-upon citation format provides a means of acknowledging authorship of new contributions to a body of knowledge. Metadata associated with educational objects is crucial to discovery. Categorization by agreed-upon fields and formats will be useful in identifying gaps in knowledge and stimulate development of advances in effective use of makerspaces in schools.

The nation has invested in makerspace hardware that collectively totals billions of dollars of equipment. Development of a library of peer-reviewed educational objects will provide teachers with resources that have been reviewed in classroom use and that can be replicated using makerspace hardware that is already in schools. Developing this capacity will lead to a more diverse range of validated educational objects that will be used in instruction across a wider range of grade levels and topics.

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