REVIEW AND RECOMMENDATIONS OF BEST PRACTICES FOR K–12 STEM LEARNING SPACES

Undertaken for the *Massachusetts School Building Authority*, under contract awarded for *RFR to Analyze Space, Configuration and Use Standards for Science and Technology/Engineering Educational Space in Massachusetts K–12 Public Schools*

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EXECUTIVE SUMMARY

This report provides an overview of best practices for science, technology, engineering, and mathematics (STEM) education as it applies to the use and design of STEM learning spaces. A well-designed space can enable hands-on science and engineering, relevant and applied mathematics, and effective integration and use of technologies. Quality STEM education begins early to foster the interest, engagement, and development of students who will be ready to contribute to a literate society, viable economy, and sustainable world.

STEM learning spaces support investigating and making experiences for *all* students, flexible and varied curriculum, and student safety. Typical STEM curricular strategies include collaboration, critical thinking and problem solving, project-based learning, and technology use. STEM instructional design blends a variety of strategies for any particular learning goal. STEM spaces must be flexible to meet such diverse modes of learning and variety of strategies.

The report provides recommendations for several types of STEM learning spaces:

- Well-designed generalist elementary classrooms include at least two sinks, display space for student work, and significant floor area for messy work.
- Elementary schools that provide a dedicated teacher for science and technology/ engineering instruction may also provide a dedicated room that provides enough space, flexibility, and design features for safely engaging in inquiry and design activities.
- The needs for a middle school science lab are similar to those for a high school lab. Key features of the 2011 MSBA high school science lab guidelines should apply, including space, perimeter utilities, and flexibility, but not include gas and fume hoods.
- Technology/engineering labs (including makerspaces) are also well served by the 2011 MSBA high school science lab guidelines, with particular considerations such as dedicated tool exhaust or tool and material storage.

The expansion and inclusion of engineering is one continuing trend that STEM space design must account for. This includes the need to support learning and experiences with key engineering design components, such as ideation and design, prototyping and fabrication, assembly and testing, and display and communication of solutions. This can be supported by making small adjustments or additions to traditional science spaces, incorporating dedicated spaces such as makerspaces, and/or provision of project spaces.

Every STEM program must carefully attend to student safety in the process of learning. The policy and cultural context of a school are a large influence on how safety is attended to and approached. Implementation of a culture of safety is only possible when the school and district works together rather than leaving safety to individual teachers or departments. Safety also requires attention to the design, maintenance, and use of key systems, such as ventilation, chemical storage, and emergency response systems. The design of school and classroom systems require a strong understanding of the intended uses of the space, and what procedures, chemicals, equipment, and materials are anticipated in the curriculum.

REVIEW CONTEXT

This report provides findings and recommendations resulting from a review and analysis of current national, Massachusetts, and Massachusetts School Building Authority (MSBA) standards and best practices for science, technology, engineering, and mathematics (STEM) learning spaces.

Goal of the review

The goal of this review, as established in the MSBA RFR of October 2017, is to:

- Complete a review and analysis of K–12 core academic STEM learning spaces, with a focus on K–8, and provide recommendations for "best practices" for the quantifying and sizing, configuration, outfitting, management, maintenance, and use of STEM learning spaces.
- Recommended "best practices" will include a list of suggested teaching and safety equipment, materials, and practices that are optimal and age-appropriate for providing core academic STEM programming for K–12.

Review process

<u>Key topics investigated</u>

The findings and recommendations presented in this report are the result of investigating a number of key topics, including:

- Best practices for K–8 STEM education
- Implications of state STEM learning standards for STEM program design
- School use of the 2011 MSBA high school science lab guidelines[1]
- Analysis of schools that include or are planning a makerspace
- Potential of conducting K–8 STEM education without hazardous chemicals
- Specific safety system recommendations (e.g., inclusion of shower drains, acid neutralization)

<u>Summary of the review process</u>

Key activities in this work have included:

- A review of documents and position statements relevant to STEM learning spaces and best practices for STEM education
- Site visits to a variety of Massachusetts schools
- Stakeholder interviews on space design and use, makerspaces in particular, and safety practices
- Regular discussion with MSBA staff

Input on best practices identified during this review, and on initial findings, were provided through sessions at a number of events in the state, including:

- MSBA Designer Roundtable

[1] Found at www.massschoolbuildings.org/programs/science_lab/guidelines

- MA Science Education Leadership Association (MSELA)
- MA Association of Science Teachers (MAST)
- MA STEM Summit

A full overview of the review protocol, site visit guide, sites visited, and organizations consulted can be found in the Appendix.

Limitations of this review

This review is focused on learning spaces that engender learning of science, technology, engineering, and mathematics learning standards. A primary focus is on K–8 learning spaces that provide for STEM teaching and learning, including both generalist classrooms and STEM-specific rooms. Second, the review considers implications of emerging trends in technology/engineering spaces, such as makerspaces. Finally, the review recommends potential updates to the 2011 MSBA high school science lab guidelines.

This review does not look at nor provide recommendations for the design of:

- Secondary level specialized STEM spaces (e.g., audio/visual production, CAD rooms, biotech labs)
- Career preparation spaces (e.g., Chapter 74 or Perkins CTE programs or vocational shops, Fab Labs)
- Outdoor learning spaces
- Art spaces (or art in the context of STEM, often referred to as STEAM programming)

This report summarizes some best practices with regard to STEM learning spaces, and some applicable codes and regulations, but the District is responsible for the operation of school buildings, practices and routines, and safety requirements. It is the District's responsibility to ensure the proper use of any educational space, that schools are in compliance with all applicable codes and regulations, including but not limited to OSHA/ANSI requirements, and to provide adequate staff training and oversight.

STEM in Massachusetts K–12 schools

All STEM education programs start with a vision of how STEM knowledge and skills will contribute to a student's future. This vision can vary widely from program to program. Whatever the visionary perspective, the design of a corresponding program – including educational strategies, curricular options provided, and built environment– should reflect that perspective. Schools must clearly articulate their vision, program, and learning goals for STEM in order to inform their educational approach and design decisions. This often takes significant time to articulate and implement. The challenge in the design of building space is to allow for a reflection of a current vision while maintaining flexibility for adjustments and unanticipated changes in the future. In order to accommodate the wide variability in perspectives and future uses, this review emphasizes a select number of goals, strategies, and choices about learning spaces that are both common to, and shown to be effective in, a wide variety of STEM programs and contexts.

Goals for STEM education

STEM education, which can incorporate subjects of science, technology, engineering, mathematics, and computer science in a variety of designs, is increasingly a focus of public education in Massachusetts. While there are different conceptions of what constitutes "STEM" across the state, it is important that each of the subjects be attended to in a K–12 educational program to prepare every student for success in an increasingly technical society and workplace (AAAS, 1993; ITEEA, 2017; NRC, 2012, 2006). Our educational system is beginning to move beyond the typical focus on mathematics and traditional sciences as separate and distinct subjects, toward more connections among the disciplines, in order to reflect the need for a literate society, an economically viable workforce, and the ability to address global challenges.

Key goals for a literate society

- Every individual will be able to understand and analyze the natural and built world to achieve personal well-being and functional communities (e.g., programming home systems, appreciating greenspace, assessing food options).
- Every individual will be able to participate in civic government, contribute to decisions about technical and scientific infrastructure, initiatives, and policies (e.g., town sewer systems, genetic testing, climate change mitigation).

Key goals for economic viability:

- Preparation of each individual for workforce viability and success in an increasingly technical and innovation-driven economy
- Development of key skills and habits of mind to successfully contribute to Massachusetts' economy:
    - Adaptability and flexibility
    - Critical analysis to evaluate claims, products, and trends
    - Ability to learn and act when change is required
    - Ability to use and apply technology and data

Key goals for global sustainability:

- Ability to contribute to grand challenges of our time which are global in nature and require engineered solutions
- Development of individuals across society and workforce that can:
    - Collaborate across communities and sectors
    - Empathize with different cultures
    - Engage in critical analysis, problem solving, and constant adaptation
    - Effectively use pervasive technology for communication, collaboration, solution generation, knowledge access, and equity

The traditional focus on distinct science and mathematics knowledge is not enough to meet these imperatives. These key goals drive the dual need for conceptual understanding and disciplinary skills now reflected in all state STEM learning standards developed since 2010.

These imperatives are also the driver of increased focus on innovation, engineering design, digital literacy, and computer science across the state.

Implications of STEM curriculum frameworks

Massachusetts curriculum frameworks for STEM, including standards and guidance for *Science and Technology/Engineering*, *Mathematics*, as well as *Digital Literacy and Computer Science*,[2] primarily articulate the expected learning goals for all students. These outcomes are written such that they can be achieved through a variety of learning contexts or program designs. Additional program guidance provided in state frameworks articulate qualities of STEM programs for schools to consider as they implement their program; this guidance encourages but does not require attention to best practices for STEM programs. State curriculum frameworks do not specifically require any particular program design, curriculum, or sizing or outfitting of learning spaces.

Guidance provided in state STEM curriculum frameworks does encourage STEM learning through active learning, such as carrying out science investigations, prototyping engineering solutions, designing and testing coded programs, or applying mathematical concepts to real-world applications. These activities, when provided as active experiences for students, necessitate using a variety of materials and tools in different environments. To accomplish this, schools need to provide appropriate materials and space to be active, and to be safe while being active. The standards do not, however, specifically define what these activities are, or what materials should be used; the standards do sometimes provide *examples* and *suggestions*. For example, consider this 7th grade physical science standard:

> 7.MS-PS3-3. Apply scientific principles of energy and heat transfer to design, construct, and test a device to minimize or maximize thermal energy transfer.* Clarification Statement: Examples of devices could include an insulated box, a solar cooker, and a vacuum flask. State Assessment Boundary: Accounting for specific heat or calculations of the total amount of thermal energy transferred is not expected in state assessment. (ESE, 2016b, p. 57)

In this case, each example device has implications for the types of materials needed, the nature of the activity to be undertaken, and even for storage of the project, assuming that the school takes a physical, hands-on approach to teaching this standard. Other example devices may be considered, or limited, based on tools available to students in a particular context, or based on staff training and experience. These examples are not, however, the only devices a school may choose from, do not indicate the number of devices to be built per class, do not preclude some or all learning activities relative to this standard from being virtual or digital, nor inform any other number of curricular design decisions that need to be worked through to make for a viable instructional experience. Standards are not intended to define the STEM program for schools, or the particular activities and materials to be used, but rather to build on an overall assumption of active student learning with relevant materials.

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[2] See Appendix for links to each curriculum framework, or visit www.doe.mass.edu/frameworks/current.html.

Defining high school "laboratory science" courses
The Massachusetts Science and Technology/Engineering [STE] Framework provides guidance to districts to establish a local definition for "laboratory science" courses; there is not a state-wide definition. This designation is commonly applied to high school courses for purposes of conveying the nature of the course to higher education institutions for admissions purposes. The Framework states:

> **Defining "Laboratory Science" Courses in High School**
> The inclusion of science and engineering practices in the standards suggests that the key factor in defining a "laboratory science" course is the nature and prevalence of the active learning experience. A definition of such courses should include two critical elements:
>
> 1. A balance between open and procedural investigations in which students learn and apply science and engineering practices.
> 2. The percent of course time engaged in inquiry- or design-based experiences.
>
> Any course aligned to the STE standards, including technology/engineering courses, can be designated as a laboratory course. STE curricula should give students regular opportunities to develop distinct science and engineering practices and occasional opportunities to apply those together as a collective set of practices. A defined number of minutes, or an extra course period, can be used for—but is not the critical feature of—a lab definition. "Laboratory science" does not have to be in a laboratory; effective STE learning also occurs through field work, in a sufficiently supplied traditional classroom, through project-based experiences, in well-designed virtual courses, and in other learning environments (e.g., out of school time, see Appendix X). *America's Lab Report* (NRC, 2006), which reviewed research and best practices across the country, supports these perspectives. (ESE, 2016b, p. 152)

What is considered appropriate STEM program design is dependent on the particular program approach, curriculum priorities, course offerings, and training or experience of staff; there is no one-size-fits-all answer or approach. Each district, school, and teacher must evaluate the particulars of their work and student needs to ensure the appropriate choice of materials, equipment, learning environment, safety considerations, and best practices for each learning goal for their program.

STEM program qualities
Quality STEM education programs are generally designed to enable:

- hands-on, minds-on science and engineering (e.g., Clough, 2002; ESE, 2016b; NRC, 2012, 2006)
- relevant and applied mathematics (e.g., ESE, 2017)
- effective integration and use of technologies (e.g., ESE, 2016a; ITEEA, 2017)
- dynamic application of STEM knowledge and skills to relevant contexts and problems (e.g., ESE, 2017, 2016a, 2017b; NRC, 2005; NAE & NRC, 2014)

Quality STEM education begins early, starting in PreK, both to ensure foundational knowledge and skills as well as to foster the interest, engagement, and development of students ready for the imperatives of a literate society, viable economy, and sustainable world.

Key educational strategies in STEM

A number of curricular and instructional strategies are found in quality STEM education programs, including (e.g., Banilower et al, 2010; NRC, 2012, 2009, 2005):

- Collaboration
- Critical thinking and problem solving
- Project-based learning
- Application to relevant community, economic, and global contexts
- Technology to enhance and engender teaching and learning of above
- Explicit attention to equity and inclusion

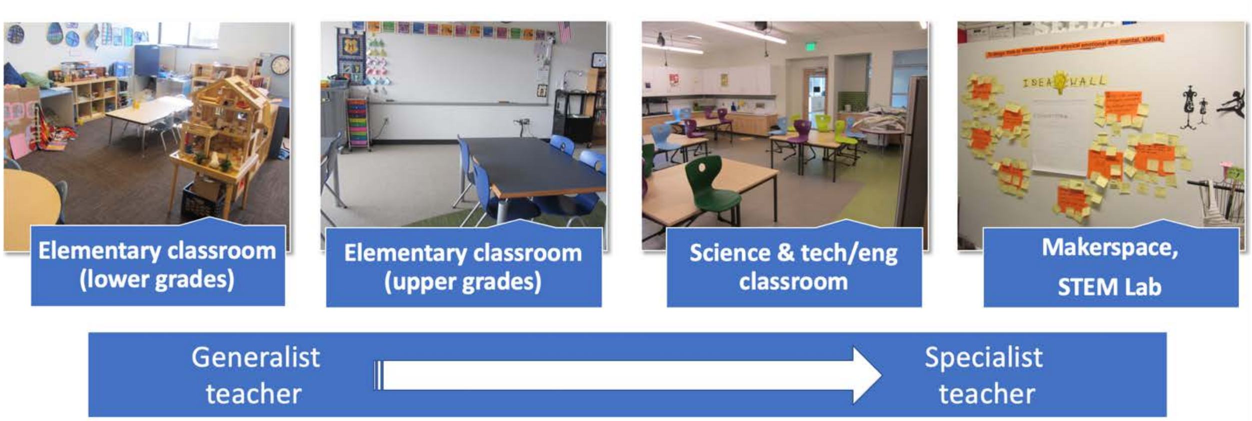
This list is illustrative of key strategies used in successful STEM programs across Massachusetts; a wide variety of additional strategies may be used in individual programs. These strategies tend to be consistent with theories of learning and instruction that enable quality STEM education, particularly:

- Social constructivism: knowledge development is an active process mediated through social interactions (Lave & Wegner, 1991; Palincsar, 1998; Vygotsky, 1978)
- Constructionism: knowledge development is facilitated when building things that are tangible and shareable (e.g., Papert & Harel, 1991)

The art of STEM instructional design is choosing among a variety of potentially effective strategies for any particular learning goal. Very often it is a combination of strategies that are woven together to best engage students in a set of experiences and tasks to achieve a learning goal. Current state STEM learning standards include an integration of conceptual outcomes and skills or practices. A lesson in high school science may, for example, include observation and measuring of a discrepant event (a counter-intuitive phenomenon) to get students thinking about a concept, a hands-on activity to explore the phenomenon further, some small group and whole-class discussion of what the students have found, and a writing or assessment task to document learning. To meet such diverse modes of learning and variety of strategies, the learning space must be flexible to accommodate regular changes in the arrangement of student groups, activity centers, learning tasks, and student performances or demonstrations.

Spectrum of elementary STEM learning spaces

This review recognizes that there is a spectrum of STEM learning spaces in Massachusetts' elementary schools (typically grades Pre-K–5). In Pre-K through grade 2, STEM learning takes place in general elementary classrooms in which the teacher is responsible for the breadth of the curriculum. This is also the case for most grade 3–5 classrooms, although at these grades some Massachusetts schools provide for teacher specialization (by, for example, teaming pairs of generalist teachers where one focuses on STEM and the other on humanities), and others provide a specialized teacher in a dedicated science specialist room (Levy et al, 2016, 2008). The decision to provide specialized STEM teachers or spaces is a program decision, not a requirement, which is a reflection of the district's philosophy and curriculum. This review provides recommendations for general elementary classrooms as well as dedicated elementary spaces that are typically staffed by a STEM-specific teacher.



Spectrum of secondary STEM learning spaces

There are a wide variety of STEM learning spaces in middle schools (typically grades 6–8) and high schools (typically grades 9–12). STEM learning opportunities are found in a variety of learning spaces such as mathematics classrooms and science labs, as well as in a wide variety of specials (middle school) and electives (high school), all of which typically have specialized teachers. In particular, technology/engineering spaces merit considerable attention in this review as this area changes regularly, often in conjunction with changes in state or local economies. Technology/engineering spaces may go by a variety of names such as technology education room ("tech ed" or "tech room"), makerspace, STEM lab, Fab Lab, and others. Science labs, technology/engineering spaces, and mathematics classrooms represent the learning spaces where the MA core academic STEM learning standards[3] are typically addressed.

[3] MA Curriculum Frameworks for *Science and Technology/Engineering* and *Mathematics.*

High schools often have a variety of specialized STEM spaces designed for particular courses or programs of studies that are not addressed in this report. These spaces can address subjects as diverse as forensics, aquaculture, broadcasting, video production, and others. Career preparation spaces are also found in many high schools, whether in comprehensive or vocational schools (such as Career and Technical Education [CTE] programs[4]). This review does not address the particular needs or designs of these spaces as they typically address curriculum beyond core academic STEM learning standards.

Evolution of making in Massachusetts schools

Makerspaces are an emerging trend in STEM education in Massachusetts schools and are a particular focus of this review. Contextualizing the trend of "maker education" (e.g., Clapp et al., 2017; Halverson & Sheridan, 2014) helps understand how it relates to current offerings in schools, particularly technology education offerings. This section lays out how making in Massachusetts schools has evolved over time in response to the state's changing economy. In this context, makerspaces are not a new category or type of space but are an iteration of spaces with a long tradition in Massachusetts schools that reflect the availability of new tools, techniques, and priorities.

<u>Foundations for making</u>

The importance of making in MA schools is often driven by personal, educational, and economic perspectives:

- At the individual level, making enables our personal ability to use basic tools and address everyday needs (e.g., enable self-sufficiency)
- At the curriculum level, learning through doing is an important contributor to effective learning (e.g., social constructivist and constructionism learning theories)
- At the program level, making is typically driven by the economy (e.g., industrial arts to support an industrial economy)

<u>Changing perspectives of making</u>

The rise of engineering design, computer science, and digital tools in education over the past decade reflects an increasing recognition that individuals need to understand the designed world they live in, and that they need to be prepared to interact with and manipulate designed systems for success in a constantly changing economy. Relatively rapid changes in the local and state economy push schools and districts (particularly in grades 6–12) to respond by regularly adding new program elements or transforming existing elements. While there has long been a core value for making in schools, how that is framed for students and what the program looks like are continually in flux. There has been an evolution of making in Massachusetts over the past approximately 50 years which can be characterized by a transition through three models.

Industrial arts model

In 2001, Massachusetts adopted a new set of Science and Technology/Engineering standards, reflecting the first time that engineering was included in the core academic disciplines and

[4] CTE programs designated and funded through Massachusetts Chapter 74 and federal Perkins programs.

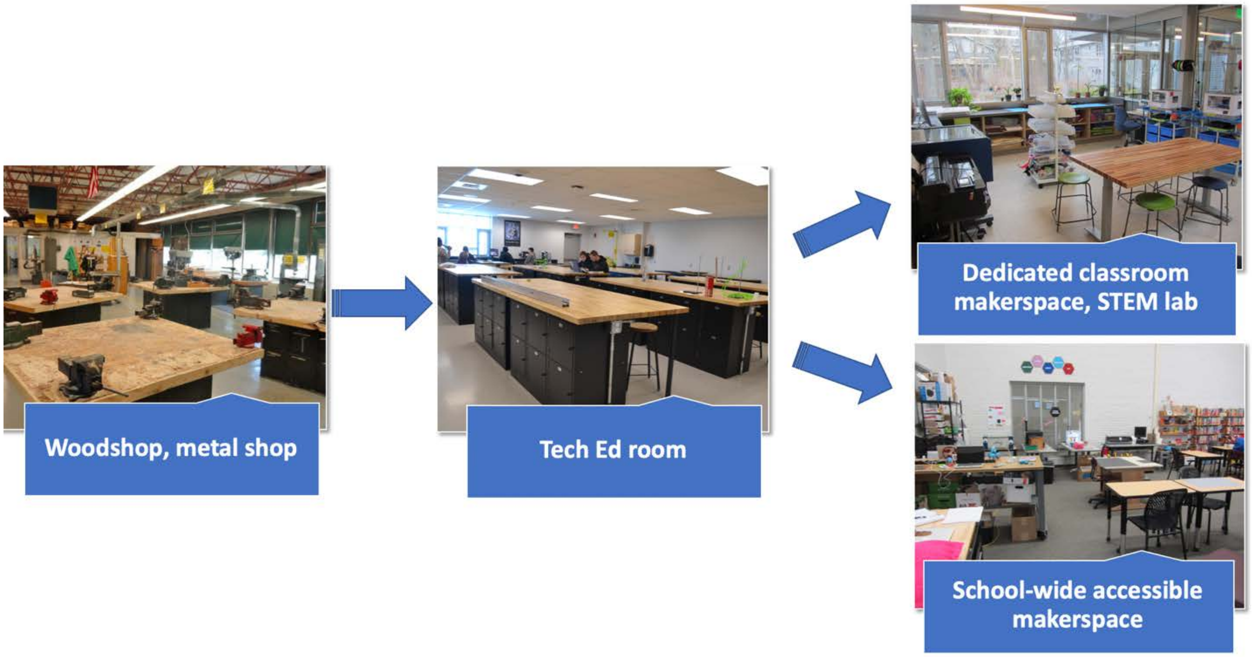
acknowledging the importance of students need to understand the technological systems our society relies on. Before the adoption of those standards, the predominant spaces for making in secondary level schools were Industrial Arts shops, characterized by now well-recognized woodshops and metal shops. In this model, the main emphasis was on production, including the use of tools to produce quality products, and skills that could be transferred to an industrial production-focused economy. These courses were generally considered specials or electives for students. Relatively large mechanical shops with major machines (tools) and systems representative of target industries were at the center of these programs, and the curriculum typically put an emphasis on quality of associated products. Additionally, programs such as family and consumer science provided opportunities for making in additional domestic and workforce contexts. Some schools still maintain courses aligned with this model.

Technology education model
With the adoption of the 2001 standards, a technology education model has been predominant in Massachusetts schools. In this model the emphasis is on major technological systems (e.g., building, transportation, communication systems) that comprise the designed world, with engineering design as a powerful process to design technological products (ITEEA, 2017). Since 2001 schools have been transitioning industrial arts shop programs to accommodate learning of the academic standards for all students through a variety of technology education offerings (often referred to as "tech ed" courses). These courses have typically been maintained as specials or electives. Learning spaces in this model have continued to include machines (tools), but the curriculum relies less on full-scale machines and products, instead allowing for smaller learning spaces with hand and power tools and a focus on engineering design process as applied across technological systems. This model de-emphasizes the quality of particular products to focus on student understanding of technological systems in the designed world.

Innovation economy model
Since about 2015 education in the state has begun to see another transition toward innovation as a central focus. This transition has not been correlated with a particular change in state learning standards, but is more reflective of policy and economic changes in the state such as the move toward advanced manufacturing and biotechnology. The emergence of an "innovation economy"[5] requires students who can address and respond to societal and economic needs through quick innovation and prototyping. Schools have begun looking for opportunities across the curriculum to integrate more of a process focus, including engineering design and prototyping, to prepare students. Learning spaces to support this model focus on collaboration and sharing tools, inclusion of a wide variety of materials and small-scale mechanical and digital tools to quickly prototype and test solutions, and flexibility for regularly changing projects or contexts. Attention to technological systems and engineering design, the focus of the technology education model, remain, but are no longer the main focus. While the specific purpose and design for learning spaces in the innovation model vary based on context, they tend to aim for broader integration across the curriculum with a focus on innovation and application. Included machines reflect a mix of some traditional tools (typically benchtop

[5] For example, see www.masstech.org/index.

machines and hand tools) and a wide variety of digital tools and technologies (e.g., robotics, 3D design and printing, laser cutting).



Visual representation showing the evolution of spaces for making in secondary schools.

The general evolution of the field through these three models represents movement toward increasing democratization and access to technology and engineering for all students (Halverson & Sheridan, 2014; Papert & Harel, 1991), with increasingly stronger ties to core academic learning standards. Given this trend, this review particularly attends to how schools can support an innovation focus, including considerations for best practices and learning space design. This review also assumes that the inclusion of technology and engineering education into core academic programming is likely to increase over time, particularly as schools continue to address the most recent Massachusetts state *Science and Technology/Engineering* standards (2016), and the *Digital Literacy and Computer Science* standards (2016), which together reflect the increasing focus on the economic and global imperatives for STEM education.

Approaches to making in MA school programming

Making as part of the core academic program in MA schools is often achieved in a school's technology/engineering programming. Elementary schools typically have the generalist classroom teacher address all the academic subjects, including technology/engineering. In secondary schools making is often reflected in the school's "technology education" course offerings.[6] In most secondary schools there is a dedicated technology/engineering teacher, but some schools integrate technology/engineering units and lessons into science or other subjects.

[6] Experiences with making are also provided through specialized STEM courses, CVTE programming, and art courses which are not a focus of this review.

Some secondary schools are moving toward more integrated science and technology/ engineering departments, bringing together two traditionally separate science and tech ed departments. The approach to making in any particular school should reflect the goals of their educational program, staff capacity and training, and availability of appropriate space and equipment.

Those schools that do not have dedicated technology/engineering staff or space can consider solutions such as:

- Rolling maker carts[7] to provide selected tools and materials conducive to integrating engineering design and prototyping into other subjects
- Outfit classrooms, science labs, or art rooms to support engineering education with:
    - collaboration and display space
    - ceiling anchors to suspend projects
    - small tools for prototyping and solution testing[8]
- Open project space created through strategic adjacencies or a dedicated "project room" for long-term or larger-scale projects

Each of these can support engineering design and innovation in non-dedicated spaces.

A rolling maker cart (left), and a large open hallway space that can be used for project-based learning activities (right).

[7] E.g., www.communityengineering.org/portablestudio/
[8] See further details relevant to this strategy in the learning spaces recommendations section below.

A specific technology/engineering space can be the right solution for those schools that have defined technology and engineering curriculum as part of the core academic program and dedicated staffing to support it. These spaces should provide programming aligned to the academic learning standards and appropriate to the grade span using it, including appropriate mechanical and digital tools, materials, and safety solutions, as well as a staff person responsible for the safe use and maintenance of the space. Use cases for this model include:

- An elementary makerspace available to all classes where work in the space enhances school-based projects and other academics. In this model, the space can be treated as a library or media program, or as a special with students scheduled into it several times a week for some portion of the school year.
- A library- or media-based makerspace in a middle or high school where classes schedule time to work on aspects of projects and supplement core academic coursework with making activities. In this model, the space is treated as a library or media program with students using it when relevant to particular projects and activities.
- A dedicated middle or high school technology education or engineering room in which a defined technology/engineering curriculum is taught. In this model, the middle school room is often treated as a special (students typically scheduled into it one quarter per year); the high school room would typically be treated as an elective for students.
- A high school science lab that is outfitted for engineering, such as robotics. In this model, the course would typically be treated as an elective course.

Makerspace in a middle school library (left) and a dedicated K–8 makerspace (right).

All schools, even those without a technology/engineering element to their current program, should plan for a time in which this will be included in their program. This does not, however, mean that all schools need to build a dedicated space. The decision to include a dedicated space or not should reflect how prominent engineering education is in the school's STEM program, how effectively engineering education is integrated into other subjects of the academic curriculum, and whether there is dedicated staff for it. Significant technology, engineering, making, and computer science education can be accommodated through minimal design elements and equipment purchases for elementary classrooms, science labs, mathematics classrooms, and/or art spaces to effectively support technology/engineering education. There are many options available, and planning should provide for program flexibility into the future.

BUILDING DESIGN AND BEST PRACTICE RECOMMENDATIONS FOR STEM LEARNING SPACES

Key assumptions for STEM learning spaces

Descriptions of and recommendations for each STEM learning space presented below all have several key assumptions in common:

- Investigating and making in school is important for students of all ages
- Flexible use and configuration of space is critical
    - Program elements will change (focus or design, courses, curriculum, instructors, projects, equipment, and daily learning experiences)
    - Technology for learning and collaboration will change
    - College and career goals and needs will change
- Student safety is a critical responsibility
    - Doing and making incur risks, and each risk must be assessed and minimized as much as possible in the context of its contribution to achieving learning goals
    - Sufficient space is needed to safely learn and engage in learning experiences
    - K–5 STEM education programming can be conducted without the need for hazardous chemicals; this should be reflected in school policy
    - All schools should use as few hazardous chemicals as possible, choosing the safest, healthiest, and most sustainable options available
    - When hazardous chemicals are used in middle and high schools, use as low volumes and as diluted solutions as possible
    - Hazards posed by tools, machines, materials, and processes must be evaluated and communicated
    - Proper safety equipment and procedures must be in place for any given learning experience
    - Proper training of staff and continued professional development is necessary to successfully and safely conduct STEM learning experiences

Safety is discussed in greater detail later in this report, including the implementation of the Occupational Safety and Health Administration (OSHA) standards to Massachusetts public employees[9] and the definition of hazardous chemicals. These assumptions apply to other aspects of the school program beyond STEM, although that is not explored in this report.

Design Guidelines by Room Type

This section considers each type of STEM room found in schools now, and likely to be typical STEM spaces into the near future. The list presented in this section offers key foundations for planning STEM spaces to meet program needs, but is not exhaustive. Descriptions of each room type provide a brief overview of their use and key features, including current assumptions of typical use. These are descriptive of how the rooms are likely to be used currently and into the

[9] malegislature.gov/Laws/SessionLaws/Acts/2018/Chapter44

near future while providing for flexibility for changes in use over longer time periods. Each section also provides recommendations for building design and best practices.

- *Building design recommendations* are those elements that must be considered in the design and construction of the building as they are building features or systems that are difficult or costly for the school to change after construction is complete.
- *Best practice recommendations* are those elements that are relatively easy to swap out or change; they are more about particular program choices or procedures a staff can implement.

All recommendations are meant to convey best practice and inform action; this report does not define MSBA policy or guidance.

Elementary generalist classroom (typically grades Pre-K–5)

Generalist elementary classrooms are built on an operating assumption that all core academic content is taught in the classroom by the generalist elementary teacher. Ideally, the curriculum integrates the subjects to make learning a coherent experience for students. Many methods can be used to teach elementary STEM in an experiential way, providing opportunities to use and manipulate a variety of materials and tools, applying learning to relevant situations and designs.

Physical features supporting STEM education in elementary generalist classrooms is primarily a function of furniture, fixtures, and equipment. In Pre-K classrooms, it is typical for a portion of the room to be dedicated to exploration and play, with blocks, water table, bubbles, or other hands-on explorations, with floors that are easily cleanable to accommodate occasional mess. Science is typically taught within K–2 generalist classrooms, and often taught in grades 3–5 generalist classrooms. In these classrooms flat tables that can be moved or grouped provide space to investigate and design, counters and windows provide opportunities for plants or small aquarium tanks, and sinks provide health and hygiene during projects and throughout the curriculum. Additional considerations here should include additional storage space for kits and materials, and a portion of the space with appropriate flooring materials in “wet areas”. Often adjacent spaces such as hallways and break-out rooms can allow for additional flexibility during project work or collaborative work.

This review assumes that STEM programming at grades Pre-K–5 can be conducted without hazardous chemicals,[10] so significant chemical safety systems or hazardous material storage are not needed. No use of open flames is also assumed, so no fire blanket is needed.[11] That said, all classrooms should contain basic safety equipment relevant to the school’s curriculum program and typical activities (such as splash goggles for eye protection). Operational training for staff should be required for all provided equipment.

[10] With the possible minor and infrequently used exceptions such as vinegar; see discussion of this in the safety policy section below.

[11] Consult local fire safety officials as many variables determine the fire safety systems needed in a space.

Building design recommendations:

- Include at least two (2) sinks, one (1) compliant with the Americans with Disabilities Act (ADA); one (1) deep and wide, with hot and cold running water and soap
  - Supports comprehensive approach to health & hygiene as well as active STEM learning activities, including project-based learning[12]
- Provide display space for projects
  - E.g., whiteboards, tack boards, shelves, ceiling anchors
- Provide a significant area with appropriate flooring materials for messy work
- If there is *not* a dedicated science and technology/engineering room or project room in the school, consider these additional design elements to support generalist classrooms:
  - Provide a counter in each classroom with outlet for a terrarium, aquarium, plant station, etc, and/or a window plant rack
  - Provide storage for projects in progress as well as science, engineering, and math materials/kits (a shared closet or small storage room accessible to all teachers[13])
- Access to outdoor learning spaces, such as natural area, garden, weather station, or outdoor classroom

Best practice recommendations:

- Moveable, flexible desks and furniture with flat surfaces
- Access to appropriate tools for investigation and design (e.g., magnifying devices)
- For young grades (Pre-K–K), include tactile exploration stations that can be swapped out during the year
  - E.g., sand table, water table, block station for building structures
- Basic safety equipment
  - Splash goggles[14] for eye protection (can include a sanitizer cabinet)
  - Fire extinguisher if required
- Technology connectivity, LCD or other interactive display(s)

[12] Consider application of this recommendation to any space in the school where health and hygiene is an important consideration or project-based learning drives curriculum design.
[13] Some districts – typically larger districts – maintain a district-based distribution center so that large kits are sent to individual schools as needed. Where this exists, there is typically not a need for additional storage space for kits in the school.
[14] Goggles should meet ANSI standard (Z87.1) for impact resistance.

Elementary science and technology/engineering room (typically grades 3–5)
Some schools choose to provide a dedicated space and staff for science and technology/engineering instruction when that fits their curriculum (Levy et al, 2016, 2008). Such rooms, often referred to as science specialist rooms, are typically in upper elementary grades (grades 3–5). Sometimes grade 6 is included in elementary schools as well, in which case a grade 6 science lab in the elementary school may reflect the design outlined in this section. Grades Pre-K–2 curriculum is generally integrated and the types of investigations are more easily accommodated in generalist classrooms. Schools that include a science and technology/engineering room should support that approach with a dedicated, relevantly-licensed teacher.

This review assumes that elementary school STEM programming can be conducted without hazardous chemicals, so significant chemical safety systems or hazardous material storage are not needed. No use of open flames is also assumed, so no fire blanket is needed.[15] That said, all science and technology/engineering classrooms should contain basic safety equipment relevant to the curriculum and typical activities (such as splash goggles for eye protection). Operational training for staff should be required for all provided equipment.

Elementary science and technology/engineering specialist rooms.

Building design recommendations:

- 45 ft^2 per student[16] (1080 ft^2 for 24 students)
- Prep/storage room: 100–150 ft^2 (for a total area of approximately 1200 ft^2)
- Usage assumes students are scheduled in room twice per week, with a typical teacher schedule of (6) 45-min sessions per day
- Counters (lab surfaces) with sinks and power outlets *on periphery of room*, appropriately sized for the grade level

[15] Consult local fire safety officials as many variables determine the fire safety systems needed in a space.
[16] Consistent with National Science Teachers Association [NSTA] recommendation (Motz et al, 2007, p. 30).

- Eyewash station(s) (minimum of 1)
- Electrical drops from ceiling to accommodate tables in center of room
- Provide a counter with outlet for a terrarium, aquarium, plant station, etc, and/or a window plant rack
- A variety of cabinets and shelves for storage and display
    - At least some should be lockable
    - Consider some open shelving or cubie style storage for student projects or student-accessible materials
- Provide varied display space for projects (e.g., whiteboards, tack boards, shelves, ceiling anchors)
- Appropriate flooring materials in wet areas
- Access to outdoor learning spaces, such as natural area, garden, weather station, or outdoor classroom

<u>Best practice recommendation:</u>

- Moveable flat-topped tables, appropriately sized for the grade level
    - Standard desk-height tables and/or counter height tables that align with perimeter counter heights appropriate for the given grades
- Relevant tools for investigation and design activities, such as microscopes
- Splash goggles[17] for eye protection (can include a sanitizer cabinet)
- Fire extinguisher if required
- Technology connectivity, LCD or other interactive display(s)

[17] Goggles should meet ANSI standard (Z87.1) for impact resistance.

Middle school science lab (typically grades 6–8)

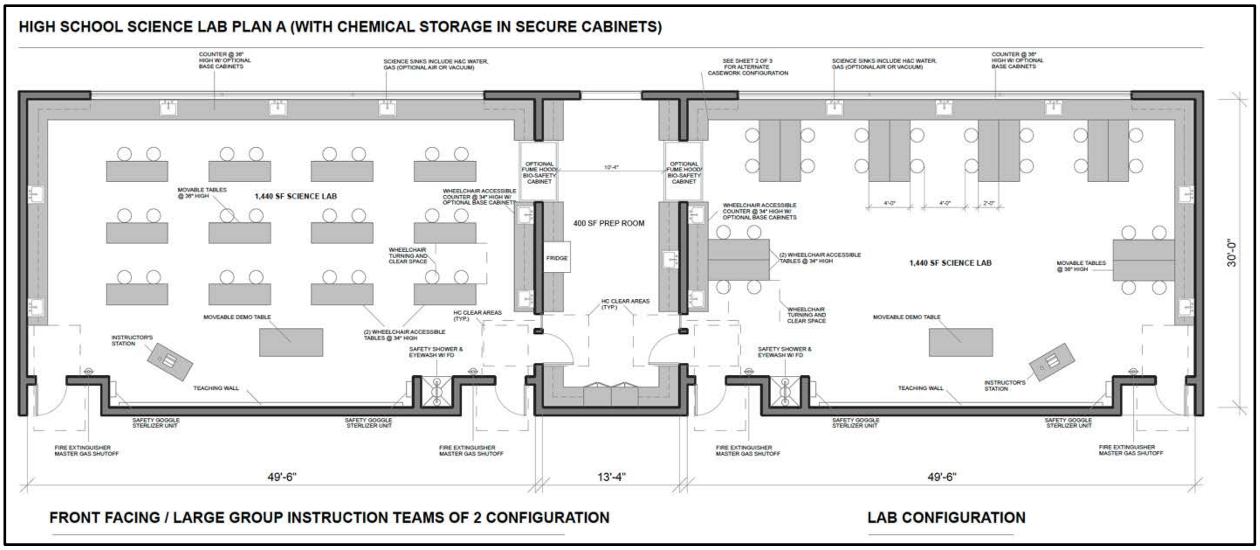
Middle school science addresses a wide variety of phenomena and concepts, and students work toward increasingly complex science practice skills. The phenomena studied span from the atomic level to solar system dynamics, include chemical phenomena such as endo- and exo-thermic reactions (grade 6) and the study of properties of chemicals resulting from reactions (grade 8), biological processes in the body and ecosystem, and application of science concepts to design challenges. In many ways, the needs for a middle school science lab are similar to those for a high school lab. Key to a functional lab is a flexible design for a variety of activities and investigations, integration of technology/engineering, and utilities to support hands-on work. Those who have worked in grades 7 and 8, in particular, recognize the wide range in stature of middle school students, often comparable to high school students. Key references on space requirements for safe science labs, including NSTA (Motz et al., 2007), treat middle and high school as equivalent.

An appropriate middle school science lab should be modeled on the 2011 MSBA high school science lab guidelines (www.massschoolbuildings.org/programs/science_lab/guidelines), including 60 ft^2 per student[18], utilities on the perimeter, 2 exit doors, moveable furniture, and so on, but with a few key differences:

- No need for gas (or any open flames) at middle school (can meet curriculum needs with hotplates).
- May want higher proportion of lab tables and/or counters at 28”–34” (rather than 36”) to accommodate wider variation in student size; movable tables and perimeter counters should align in height (be mindful of ADA and MA Architectural Access Board [MAAB] requirements that require a maximum 28”-34” height and a minimum clear space below the counter of 27” for accessible surfaces).
- Only 1 fume hood in the chemical storage area for preparation and handling purposes. Classroom activities at the middle school should not involve students in handling chemicals that require the use of a fume hood. Other classroom chemical safety systems, including eyewash station, deluge shower, and negative room pressure, should be maintained for emergency response.
- A chemical storage room at middle school can be smaller than provided for in high school given the fewer number and amounts of chemicals, while still providing for key safety features of a chemical storage room.

[18] Consistent with National Science Teachers Association [NSTA] recommendation for middle school (Motz et al., 2007, p. 30).

High school science lab (typically grades 9–12): potential updates to 2011 MSBA guidelines
A number of potential updates to the 2011 MSBA high school science lab guidelines[19] have been identified following visits to several sites that now use this model.



Partial view of the 2011 MSBA Science Lab guidelines.

<u>Suggested updates to guidelines:</u>

- Ensure the prep room is wide enough to allow for both counter (with cabinets) and deep storage shelves. ADA/MAAB requires a minimum 36" clear width for wheelchair passage throughout the space, and a minimum 60" diameter circle for wheelchair turnaround somewhere within the space. Assuming the full 60" clear between base cabinets throughout, the result would be a minimum of 7' clear between walls if there are base cabinets on one side, and 9' clear between walls if there are base cabinets and/or deep shelves on both sides. Note that the MSBA HS Science lab guidelines (with base cabinets on both sides) show 13 feet 4 inches between walls.
    - The intent is to avoid thin prep rooms where the aisle in front of base cabinets is the only storage option; particularly an issue where a single lab has a dedicated, smaller prep room that is not shared

[19] Found at: www.massschoolbuildings.org/programs/science_lab/guidelines

Two science prep rooms with too many items being stored. The thin design contributes to the clutter as there is not sufficient width for counters and storage shelves or carts.

- Ensure sinks are as wide and deep as possible
    - Very narrow sinks in lab counters are not conducive to project-based work
    - Must provide at least one (1) ADA compliant sink

- Recommend that schools do *not* include an acid neutralization system or holding tank, and instead utilize best practices in chemical choices, neutralization in lab procedures, and disposal practices
    - Best practice alleviates the need for these systems (see safety section), and when best practices are not followed, these systems can result in additional hazards
    - Note that without a holding tank, no hazardous chemicals can be poured down any drain
    - Deluge showers should not include a drain (see safety section)

Thin sink in shallow counter.

- Labs must include proper procedures for storage and disposal of all hazardous waste (see safety section); none can be poured down the drain
- Consider emergency call button that rings multiple phones in central office
- Encourage inclusion of electrical drops and ceiling bars in all science labs
  - Ensures reduction of electrical hazards any time electrical equipment (e.g., microscopes, probe ware) is used at lab tables in the interior of the room
  - Adds flexibility for future use, supports engineering education

Ceiling bar (left) and electrical drops (right).

<u>Best practice recommendations:</u>

- Ensure lab tables are same height as counters on periphery
  - Mismatched heights damage cabinets if not even, pose potential safety hazard during labs
- Label all doors leading to long-term chemical storage with hazards graphic placard (see safety section)
- Provide sturdy stools
  - Labs do not need adjustable stools (those tend to break)
  - Stools should not have backs (for safety when doing labs with hazards, and to reduce risk of tipping); if stools have backs they should not be used when engaging in lab activities that involve hazards (students should stand) so they do not become a barrier to responding to a situation
- Technology connectivity, LCD or other interactive display(s)
  - Do not include monitors with articulating arms over lab bench areas as these pose a hazard

Technology/engineering lab (including makerspaces) (grades 6–12)

Technology/engineering learning spaces go by many names and take a variety of forms that are reflective of the particular program choices and relationship to other subjects.

- Technology education is a general label for a wide variety of courses, including tech shops and tech classrooms that may focus on broadcast production, culinary arts, robotics, technology/engineering, CAD design, computer science, woodshop, and many others. Can be used as a generic term that also encompasses makerspaces or STEM labs.
- Makerspaces can take many shapes and forms but have in common an intention to equitably provide maker activity to all students and promote creativity, innovation, and a culture of persistence.
- STEM Lab is, in essence, another name for makerspaces, but with a title that highlights disciplinary connections rather than a maker philosophy.
- Fab Lab predominantly refers to an MIT model of community-based invention center and business incubator.[20] While this term is intended to designate a model of career preparation beyond the scope of this review, we have seen a few schools apply this label to their makerspace or shop. We do not encourage the use of this term given the original intended use.
- Additional labels used in community or organizational spaces refer to niche designs, such as hackerspace and breakerspace, which are not generally found in K–12 schools.
- Schools may also apply a more particular label to a technology/engineering lab space to achieve unique branding (e.g., Innovation Lab; DaVinci Lab) that do not indicate the particular underlying model.

Whatever the label is used, these spaces are designed to support key engineering design components:

- ideation and design
- prototyping and fabrication
- assembly and testing
- display and communication of solutions

In this review, "technology/engineering lab" can encompass a broad range of courses or topics that includes makerspaces. Much of this analysis focuses on makerspaces in particular as these are the newest form of technology/engineering spaces, as discussed above. The variety of currently existing technology education (tech ed) courses continue to be relevant and meaningful options to advance important STEM education goals; makerspaces are just one more option in the list.

This review assumes typical programming in a technology/engineering lab, including makerspaces, can be conducted without hazardous chemicals, so significant chemical safety systems or hazardous material storage are not needed. To the extent that glues, solvents, finishes, or other chemicals may be used in these labs,[21] each should be evaluated for the

[20] For more information, visit: www.fabfoundation.org/.

[21] If such chemicals are present, ensure that Safety Data Sheets (SDSs) are provided for each.

hazard it poses and a determination made about appropriate use in this lab.[22] All technology/engineering lab spaces should contain basic safety equipment relevant to the curriculum and activities anticipated (such as splash goggles for eye protection or direct exhaust for certain procedures). Operational training for staff should be required for all provided equipment.

Makerspaces

Makerspaces are varied in their design and purpose, but several considerations are useful for any school thinking about adding a makerspace to their program:

- A makerspace can be appropriate at any grade level but most likely to be found in secondary grades
    - Projects that young students (particularly K–2) are likely to engage in are easier to accommodate in a sufficiently outfitted general classroom, a grades 3-5 specialist room, or media center that includes a makerspace component; it is rare that a K-5 school will require both a specialist room *and* a makerspace[23]
    - Equipment, tools, and materials should be differentiated by grade span
- The overall design of any particular space is dependent on the educational goals and type of activities anticipated (e.g., programming robotics and physical computing vs 3D printing and prototyping)
    - Start the design of a makerspace by attending to the learning goals and curriculum, not the space or tools
    - Aim for simplicity: a few well-chosen tools and materials can go a long way
    - Build over time as need arises and curriculum projects are defined
    - Anticipate safety measures and ventilation needs that impact the design of the space
- Technology in these spaces will change regularly so flexibility is critical

If a dedicated makerspace space is ultimately decided upon, it is critical that the school:

- Show clear commitment to the space as part of the core academic program (commitment to project-based approach or similar, and clear articulation of how the space helps achieve state STEM learning standards)
- Consider it an academic space in which a dedicated, relevantly-certified teacher will be responsible
    - A staff member has to be responsible for the integrity of the curricular program, the learning space, and safety of students
    - The makerspace should not be staffed by volunteers nor should responsibility of the space be distributed or shared among a group of staff

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[22] It may be most appropriate to use such chemicals in a different space such as a science lab outfitted with appropriate chemical safety systems. Alternatively, there may be operational means to safely use selected chemicals in limited situations; see the discussion in the safety policy section on use of hazardous chemicals in elementary schools for more on this.

[23] It is also rare that an elementary school would require both a specialist room *and* project room (see later section).

    - Without a dedicated staff person responsible for the space, these rooms tend to be underused, become unorganized and cluttered, and unsafe
- Show clear commitment to long term professional development to maximize staff's ability to successfully and safely integrate into the curriculum[24]

Makerspace use cases

Dedicated makerspaces in middle school

These spaces tend to be treated as specials, with students scheduled into it 1 quarter, trimester, or semester per year (approximately 45, 60, or 90 days, respectively).

Dedicated makerspaces in high school

Dedicated high school makerspaces tend to be treated as elective courses, with students selecting a year-long or semester-long course as part of their school-year schedule.

For middle and high schools, the number of makerspaces per school can vary but should be assessed in the context of the full set of tech ed spaces and courses.

Makerspaces in libraries, media centers, or learning commons

Common-area makerspaces are typically treated as a shared resource that is functionally part of another space; they are not stand-alone dedicated spaces (Burke, 2014). These are typically scheduled for use on an as-needed basis, often as it applies to project-based work in other classrooms. Curriculum integration with all academic classrooms may engender a wider variety of projects and needs. That said, these spaces may host regularly scheduled classes (as specials or electives) but those would be far fewer in number or frequency as compared to a dedicated makerspace. Even as a shared space, a staff person should be responsible for the space and activities within it.

Given the shared and co-located nature of makerspaces in common areas, the dual use of the area for making activities and other more traditional library or media functions are sometimes in tension with each other. Some considerations these designs should attend to include:

- Machine noise (background hum of machines can add up; operation of some machines can be a distraction)
- Collaborative project work and testing can get noisy or messy
- Tool- or machine-specific requirements, such as dedicated exhaust, are not typically available in library or media areas
- General open access requires thinking about control and monitoring of tools and materials, through the use of lockable cabinets, storage, electrical lock-out or digital login for use of machines, and storage of digital files
- Scheduling and management strategies for providing typical library or media activities in the space and makerspace activities

[24] Professional development may include out-of-school training and development opportunities as well as in-school time for planning, collaboration, and coordination.

Makerspace design recommendations

There are many similarities in the underlying assumptions for technology/engineering labs (and hence makerspaces) as are applied to the 2011 MSBA high school science lab guidelines (e.g., flexibility, perimeter utilities, 60 ft^2 space allocation per secondary student for safe activities). Technology/engineering labs, including makerspaces, should be modeled on these same guidelines.

Building design recommendations

Space:

- 60 ft^2 per student at middle and high school; 45 ft^2 per student at elementary grades
  - NSTA science lab recommends 60 ft^2 (Motz et al, 20017, p. 30), Roy & Love (2017, p. 122) recommend 50 ft^2 for fabrication areas plus significant additional space for related functions, resulting in total recommendation close to 60 ft^2
- Tool and material storage area[25]: 150–200 ft^2 for middle and high school
  - Roy & Love (2017, p. 123) recommend 150–250 ft^2
  - Large enough for 2 shelves with center aisle, map drawer cabinet or other storage options appropriate for anticipated materials and tools; lockable
- Spray booth (if included; may also be located with art classroom and shared): 100 ft^2
  - Roy & Love (2017, p. 123) recommend 100 ft^2
  - For painting or other fumes (e.g., glues or finishes)
  - Ensure the spray booth is large enough for most anticipated projects
  - Requires direct exhaust

Utilities:

- Minimum of two (2) sinks, one (1) ADA compliant, one (1) large – wide and deep, with hot and cold running water and soap
- Provide ceiling bars for suspending projects from the ceiling
- Provide sufficient electrical outlets, including ceiling drops
- Provide varied counter/bench heights (refer to ADA/MAAB requirements: 36" height is standard for standing/stool height counters, 28"- 34" is a universal height for standing and handicapped accessibility, 30" is a standard desk height)
  - Include some shorter countertops for benchtop tools (~28"–30"), as appropriate for the grade span
    - Low surfaces for benchtop tools ensure that students are looking down slightly at the work surface of the tool
- Safety equipment relevant to planned or anticipated tools, machines, and/or procedures in the technology/engineering lab
  - Basic safety equipment
    - Splash goggles[26] (with option of sanitizing cabinet)
    - Eyewash station
    - Fire safety equipment as required (e.g., extinguisher, blanket)[27]

[25] This is functionally the equivalent of a science prep room.

[26] Goggles should meet ANSI standard (Z87.1) for impact resistance.

[27] Consult local fire safety officials as many variables determine the fire safety systems needed in a space.

    - Equipment-specific safety systems[28] for
        - Direct exhaust (see list below) or activities (e.g., soldering)
        - Power lock-out so a hazardous tool cannot run unless the system is turned on with a key
        - Emergency stops in room to cut power to devices
        - Safety zones (typically 3 feet) around any machines

Storage:

- Provide a variety of storage options including closet, cabinet, and shelving options[29]
    - Lockable cabinet or closet dedicated to tools and portable machines; can be in the lockable storage closet or a lockable tall standing cabinet in the lab
    - Varied open shelving and cabinets for student-accessible materials, tools, and projects
- Stock material storage solutions (tall/long materials, sheet materials, bins for variety of smalls items), each of which can be secured for safety (e.g., such that long materials do not fall over); can be in the lockable storage/materials closet
    - Potential categories of different stock:
        - Electronic parts and tools
        - Computers, cameras, software
        - Craft and art supplies
        - Building materials (including long and sheet stock)
        - Traditional tools
        - Book and article library
- Provide varied display space to pin/hang 2D products (e.g., boards, shallow cases) and to place 3D products (e.g., shelves, deeper cases)
    - Consider displays in the lab and in hallways or school entry spaces

<u>Makerspace best practice recommendations</u>

Furniture and equipment:

- Put as much as possible on wheels – both for rearranging space, temporary storage, and so students can move materials carts and workspaces as needed to do project work
    - Moveable materials carts, tables and chairs, tools/carts, even whiteboards
- Prioritize table-top tools (e.g., scroll saw, drill press) for flexibility and efficient use of space
- Identify areas for 'centers' (e.g., electronics, sewing, vinyl design production) that can be changed on a periodic basis and as technology or the STEM program changes
- Provide small group tables rather than individual desks

Storage:

- Consider accessibility and storage of both artifacts and information. Trend toward keeping materials and work easily accessible unless they absolutely must be protected

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[28] Hazards posed by tools, machines, materials, and processes must be evaluated and communicated; follow OSHA standards relevant to mechanical tools and systems as appropriate.

[29] A good practice for makerspaces is to plan for up to 30% of available space to be dedicated to storage (Doorley & Witthoft, 2012). For purposes of this review, this is a reminder of the importance of storage, not a target.

- Security should be coordinated and integrated with the visibility necessary in a collaborative and creative context. Some storage should be visible and some out of sight
- Consider accessibility and storage for both physical and digital resources

<u>Machines and tools that many makerspaces include</u>

The following list has been generated from analysis of a variety of grades 6–12 makerspaces observed throughout this review. This could be considered a representative equipment list for a basic makerspace; actual equipment should be tailored to the particular school goals, projects, and curriculum. Items are listed alphabetically to reflect the notion that any particular tool is not important by itself, but its value is in how it contributes to educational goals. The number in parentheses reflect the average number observed in a space. Typical tools include:

- 3D printers[30] (2–3); sometimes all the same, sometimes different sizes or brands
- Assortment of typical hand tools appropriate to the grade level (e.g., hammer, screwdrivers, cutting tools, hand saw) (3–5 of each)
- Benchtop band saw or scroll saw (1)
- Benchtop drill press (1)
- Clamps of various sizes (from binder clips up to clamps several feet long; numbers vary)
- Electronics testers / multimeters (1–2)
- Hot glue guns (10)
- Laptops or tablets (5–10)
- Laser cutter (1)
- Laser printer (1)
- Sewing machines (1–3)
- Shop vac (1)
- Soldering irons (3–6)
- Vinyl cutter (1–2); small or mid-size cutter is typical; rarely a large format cutter


Sample benchtop tools.[31]

[30] The majority of makerspaces observed in this review used low temperature plastics, avoiding nanoparticles high temperature plastics can produce (www.researchgate.net/publication/308023202_3D_printing_What%27s_the_harm).

[31] All benchtop power tools must be properly anchored to the counter, and cords secured out of the way.

Equipment that typically require direct exhaust

The following equipment requires direct exhaust to the outside: [32]

- 3D printer using ABS or other high temperature material
- Biocontainment area (not common, but sometimes seen for high school biotechnology activities)
- Cooktop
- Laser cutter
- Soldering station[33]
    - In all cases avoid the use of lead-based solder
- Spray booth

Note that any tool producing significant dust (e.g., sander/grinder, table saw/chop saw) requires a dust collection system.

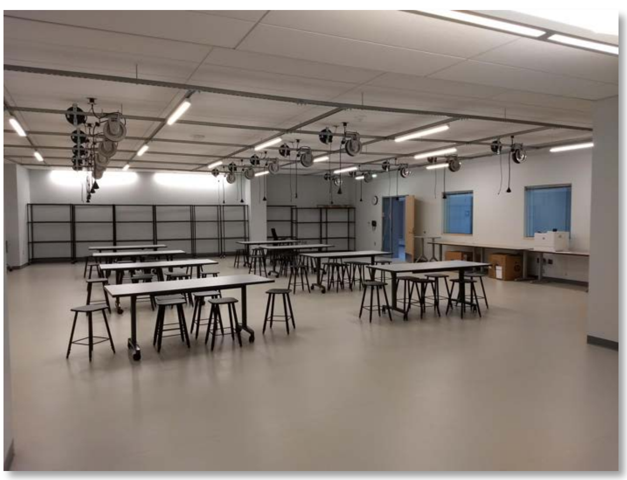
[32] Check manufacturer guidelines for specific equipment.

[33] Many makerspaces use table-top charcoal fans but that is not effective in removing fumes from the work area.

Project room (grades K–12)
Project rooms are different than technology/engineering labs and are not dedicated to STEM education per se, but can support STEM, project-based learning activities, prototype testing, and presentations. If a distinct project room is not feasible or required, project areas can be created through strategic adjacencies and/or openings (movable walls, large door openings, etc.) that provide a similar open space and flexible use for project-based work. Adjacent spaces such as hallways and break-out rooms can allow for additional flexibility during project work or collaborative work. Use of common "neighborhood" spaces can accommodate larger projects and projects involving students from more than one class working together.

Such project spaces are very flexible, with little equipment or materials beyond collaboration technology and flexible furniture. They are designed for collaborative activities such as small group work, project brainstorming, prototype and product testing, presentation and project display, and communication. Emerging uses may include virtual reality (VR) and augmented reality (AR) projects, which typically require free floor space.

At the elementary school level, a project room can be an alternative option to a science and technology/engineering specialist room, in cases where the school may not include a dedicated science teacher or specialized STE program. Many rooms within the typical middle and high school building offer opportunities for projects (e.g. art rooms, science rooms, media rooms, multipurpose rooms). In all cases, the space should be multi-purpose with a variety of uses that serve multiples aspects of the school's educational program.



Project rooms with moveable furniture and (on the left) lots of moveable shelves for storage and display and (on the right) lots of white boards and pin boards for collaboration and sharing.

Safety practices should be applied in project rooms just as in any other space where STEM activities are conducted. While investigations, design tasks, and project will be undertaken in these spaces, there should be no hazardous chemicals used in these spaces as there are not substantive chemical safety systems or hazardous materials storage provided, nor should there be any open flames as appropriate fire safety equipment is unlikely to be included. [34]

Building design recommendations:

- 40 ft^2 per student elementary (equivalent to standard classroom) (Motz et al, 2007, p. 30); 50 ft^2 per student secondary (equivalent to art room)
- Comparable project areas can be achieved via creative adjacencies using, for example, hallway space, moveable walls or large doors, or other solutions that provide for significant floor space and collaboration opportunities
- Significant whiteboard and tack/pin board surfaces
- Sinks with hot and cold running water and soap, at least one being ADA compliant
- Provide appropriate flooring materials

Best practice recommendations:

- Flexible tables for small group work and project work
- Technology connectivity, LCD or other interactive display(s), print center
- Provide some flexible storage for projects under development (combination of open and lockable storage)

Mathematics classroom (grades 6-12)

Mathematics is held in regular classrooms and typically there are no unique space design considerations. One emerging trend that may have some storage implications is the increasing use of manipulatives in mathematics, particularly in elementary and middle schools. These manipulatives are materials bundled in kits aligned to mathematics curriculum units. While not particularly large, classroom sets of these kits across a number of units can require storage space, either in class or shared across classrooms.

As is the trend in many subjects, more emphasis on varied group work and collaboration strategies requires that student furniture should be as flexible as other STEM learning spaces. Additionally, mathematics is also seeing an increase in technology use, including math apps and collaboration technology that require access and bandwidth in the classroom.

[34] Consult local fire safety officials as many variables determine the fire safety systems needed in a space.

Additional considerations across STEM learning spaces

The inclusion of sinks, storage, and digital technology each merit a brief additional discussion here given their prevalence across STEM learning spaces. These may have implications for other school spaces as well, but this discussion does not assume that sinks and storage are necessary for every space, such as for project-based learning spaces located in adjacent hallways.

Sinks

The inclusion of sinks in STEM learning spaces supports the wide variety of STEM activities typically conducted during a school year, including many activities that involve messy materials and processes or that directly rely on having a water source. STEM activities can include, for example, filling or cleaning buckets or tubs used for providing water to small stream tables, filling pitchers used to maintain a small aquarium, cleaning a small habitat container, or studying the water cycle. Readily available sinks are also a key element of doing STEM education safely, such as when students need to wash up after examining terrariums, worms, owl pellets, or other organics. Finally, readily available sinks contribute to overall health and hygiene of students, allowing for regular hand washing and clean-up of equipment.

Variety of options for sinks large enough for STEM needs and project-based activities.

The recommendation forwarded in this report is to include a minimum of two sinks in each general elementary classroom and STEM-specific learning space, where one is ADA compliant and one is sufficiently large and deep enough to handle a wide variety of STEM activities. While this report focuses on STEM spaces, the rationale presented here highlights the importance of including a large enough sink in any room where project-based learning will take place, where relatively large equipment needs to be cleaned and maintained, and wherever students need ready access to soap and water to wash their hands or equipment where such equipment will be shared.

Storage

Having adequate storage for regularly-used materials, on-going projects, and equipment that needs to be secured is critical for an effective and safe STEM program. Identifying an appropriate amount of storage for a particular learning space requires consideration of multiple elements that are often in tension with each other.

- Materials for a particular unit or project can be bulky, and only used once or twice in a school year; it is often not prudent to keep some of those materials in openly accessible areas when they are not in use (both safety and maintenance concerns).
- Ensuring that there are enough materials for a particular school year needs to be balanced with the need to store materials not in use.
- Fiscal efficiency by ordering in bulk puts a strain on the storage facilities, and can lead to expiration of some consumables (such as chemicals) that also incur a cost for disposal
- Ongoing student projects need to be stored in between classes, other completed projects are intended to be displayed for educational purposes; each requires accessible storage to students.
- Availability (or lack) of storage drive curricular decisions. For example, if no storage options are provided, curriculum will bias toward short 1- or 2-day projects vs. extended multi-day, week- or month-long projects.
- Safety – materials and objects will be "stored" in unlikely and undesirable places if there are not reasonable and appropriate storage options (Doorley & Whitthoft, 2012). Inappropriately storing things on the floor, covering student work tables, in hallways, or around safety equipment can pose significant hazards, and become an impediment to instructional activities or response to a classroom emergency.
- Some materials, equipment and tools need to be readily accessible to students, while others required controlled or even secure access.
- Storage should account for both physical resources and digital resources.
- Effective use and maintenance of storage requires ongoing review, clean-up, and organization to prevent cluttering and development of hazards that may negatively impact teaching and learning.

This report recommends that sufficient storage be provided, which is a relative judgement guided by an assessment of what materials are used and projects that are undertaken in the educational program. Unfortunately, there is no clear guidance on calculating the amount. In some instances, such as for math classrooms where manipulatives are common, wall or under-counter cabinets can be enough; in other instances, such as for technology/engineering rooms or makerspaces, a variety of storage options may be needed and account for upwards of 30% of overall space (Doorley & Whitthoft, 2012). Looking to other learning spaces and programs, such as art rooms, music rooms, theater/stage areas, or gymnasiums can provide guidance and strategies for project and material storage.

School should implement a 'just-in-time' purchasing approach for school materials, particularly for chemicals. This may be facilitated through budgetary line items dedicated for materials purchase (and/or disposal). Several districts observed in this review set up an annual materials budget line that has helped alleviate teacher concerns about materials availability and reduced the overall storage load over time. When a teacher can order needed materials each year in time for particular projects or units, this alleviates the need to keep large quantities of materials. This does not remove the need for all storage but should be considered a best practice strategy for reducing over-ordering and long-term storage of materials that may not actually be used, and reducing costly disposal of expired, hazardous materials.

Lack of storage results in room clutter, reduced teaching space, and unsafe conditions.

Digital Technology

The prevalence of digital technologies to support STEM learning is growing and will only continue to increase over time. STEM-specific technologies vary widely, but currently include items such probe ware, digital microscopes, robotics systems, and programmable computer boards, all of which are increasingly being connected to the internet. Non-STEM-specific technologies found across the curriculum also continue to increase in STEM learning spaces.

<u>Instructional set up</u>

Every STEM space should be provided with a minimum technology set-up that includes:

- LCD projector with interactive whiteboard, or large interactive LCD display
- Classroom set of tablets and/or laptops
    - For PreK–2, tablets seem to be the predominant choice
    - For 3–5, laptops seem to be more common
- Document camera
- Ability to screen cast from tablets/laptops to display
- Wireless network to allow for internet and network access anywhere in the room or school
- Charging station or cart
- Sufficient internet bandwidth (see listing of bandwidth-intensive usage next)
- Voice amplification systems for instructors
    - Both to serve those who have hearing impairments and for safety and management of all students when the classroom is noisy

<u>Bandwidth needs</u>

These are examples of technology uses that require, or will increasingly require, significant bandwidth:

- Cloud application and file storage[35] and backup
- Video-based learning (video streaming) and immersive video environments (e.g., 360 videos, VR, AR)
- Video production and sharing
- Project collaboration and teacher professional development through video-conferencing or immersive learning environments with science experts, teachers, global classrooms
- Web-based apps (e.g., virtual dissection, virtual labs, CAD design, remote telescope control, interactive apps and educational games)
- Interactive digital lessons and assessments
- School-wide or district-wide learning management systems
- Internet research
- Downloading design files (e.g., for 3D printing, 3D graphics)

[35] Core to cloud-based computing systems often used in schools, such as Chromebooks.

SAFETY IN STEM LEARNING SPACES

Considerations of safety are important elements for an effective STEM program. The goal of every STEM program should include student safety in the process of learning. Every task, activity, investigation, design, or field trip in which students engage carries some risk, but schools justify those risks based on their value and necessity to student learning. This section provides a summary of safety considerations particularly salient to this review. This is not an inclusive or comprehensive treatment of safety for STEM education. There are numerous STEM learning spaces articles, books, and websites that address safety in science and technology/engineering labs. Some resources are provided in the Appendix that schools and districts can use to develop a comprehensive approach to safety in STEM programming.

A safe STEM program identifies activities that best meet a learning goal while minimizing risk. A school or teacher can never get to zero risk – every activity engaged in, material or tool used, or field trip taken has risk. The key is to evaluate the risk, minimize it, plan for responses to unexpected situations, and justify the risk present in terms of the benefit to student learning (learning goals). Safety systems installed in classrooms or buildings are a key element of carrying out safe STEM education, but facilities cannot make up for a lack of planning, training, or best practice. Once an activity is chosen for a particular learning goal, it is incumbent on the staff and students to safely carry out the activity.

The specific design of a safety program for any school or program is dependent on the learning goals, activities to be undertaken, and materials or equipment used. For that reason, the safety program for any particular school will be somewhat unique and will change over time. There are many elements of STEM programming, however, that are common across schools and for which best practices have been identified. This section summarizes some of those that are most relevant to the design of STEM learning spaces.

Policy

The policy and cultural context that teachers and students work in have a large influence on how safety is attended to and approached. Safety must be a constant consideration (Kwan et al., 2003; NRC, 2011; Roy et al., 2017; Texley et al., 2004). Schools can promote this by:

- Establishing a culture of safety
- Actively managing hazards (all hazards, not just chemical hazards)
- Maintaining plans and protocols
- Conducting a risk assessment for each instructional activity
- Conducting worst-case planning and training
- Provide safety orientation and practices
- Regularly inspecting tools, materials, and processes
- Regularly maintaining and updating tools and equipment
- Provide experienced personnel dedicated to the ongoing review of safety and spaces

- Provide continuing professional development to increase safety awareness and expertise for all staff

Federal, state, and local policy also plays a role in the design of safe STEM programs. In Massachusetts, for example, regulatory references include requirement of OSHA protections for all employees, fire prevention regulations, Right-To-Know law, hazardous waste regulations, and building codes, to name a few.

Duty or standard of care for safe STEM education

Core to the educational endeavor in Massachusetts is the principle that each district and school is responsible for providing a safe learning environment for students. Educators and administrators have a "Duty of Care" – an obligation, recognized by law, requiring conformance to a certain standard of conduct to protect others against unreasonable risk. For STEM educators and administrators, this includes providing safety information and training to educators and students and communicating potential hazards to all stakeholders, including parents and the community. One way to address this is to apply all district and school safety policies, plans, procedures, and best practices to all students as well as employees. Additional considerations, such as safety training or safety contracts for students may be needed. Make each element of this approach explicit in district and school policy.

Implementation of OSHA protections for MA public employees

In March 2018, An Act Relative to Standards of Employee Safety was signed into Massachusetts law.[36] This makes explicit that public employers shall provide public employees at least the level of protection provided under the federal Occupational Safety and Health Act (OSHA) of 1970. While not a new expectation for Massachusetts, making this explicit will raise awareness for schools and districts across the state, and require implementation for STEM educators and programs. For example, having and maintaining a current safety policy, a comprehensive safety plan, a chemical hygiene officer, and following best safety practices in alignment with OSHA expectations will be new for many academic STEM staff.

Of particular focus for STEM programs is the OSHA Laboratory Standard (29 Code of Federal Regulations [CFR] 1910.1450) and the Hazard Communication Standard (29 CFR 1910.1200), both of which address hazardous chemical use in schools. While there are many other hazards that need to be attended to and that are addressed by OSHA protections, hazardous chemicals (as defined in 29 CFR 1910.1200, see subsequent section below) have particularly large implications for worker safety and safety systems. Other OSHA standards set expectations for the evaluation and mediation of a wide variety of other hazards (e.g., noise, dust, sound, electrical, physical). Each should be part of a school safety assessment and plan.

<u>Hazard Communication Standard (29 CFR 1910.1200)</u>

This standard is designed to ensure that chemical hazards are identified and communicated to those who may be affected by them. All school activities involving chemicals must meet the

[36] malegislature.gov/Laws/SessionLaws/Acts/2018/Chapter44

Hazard Communication Standard, whether that is in the science lab or as part of school cleaning and maintenance. Key elements of the hazard communication standard include:

- Development and maintenance of a written hazard communication program for the workplace, including lists of hazardous chemicals present
- Ensuring that containers of chemicals in the workplace are properly labeled
- Ensuring that safety data sheets (SDSs) for chemicals that workers may be exposed to are made available to workers[37]
- Development and implementation of worker training programs regarding hazards of chemicals they may be exposed to and the appropriate protective measures that must be used when handling these chemicals (Hazards Communications [HazCom] training).

<u>Laboratory Standard (29 CFR 1910.1450)</u>
A particularly important consideration for STEM programs is whether STEM learning activities that involve hazardous chemicals fit the OSHA Laboratory Standard, which has 4 considerations:

- Use of multiple chemicals or multiple procedures
- Work is done on a lab scale; what an individual will do (not production scale)
- The workplace is not a production facility
- There is standard safety equipment present

Most STEM education activity that uses hazardous chemicals would meet these 4 criteria and therefore be expected to fulfill the Laboratory Standard.[38] Meeting this standard has significant implications for training and procedures in the STEM learning space in order to protect people working in those spaces. Fulfilling the expectations of the Laboratory Standard consists of five major elements:

- Hazard identification
- Chemical Hygiene Plan (and Officer)
- Information and training
- Exposure monitoring
- Medical consultation and examinations when necessary

This report does not provide additional details about these elements; a variety of references and resources are available to assist schools in determining appropriate actions (selected references are listed in the Appendix).

Avoiding or reducing hazardous chemicals in schools
<u>OSHA definition of hazardous chemicals</u>
The definition of hazardous chemicals provided by OSHA (29 CFR 1910.1200) is:

> *Hazardous chemical* means any chemical which is classified as a physical hazard or a health hazard, a simple asphyxiant, combustible dust, pyrophoric gas, or hazard not otherwise classified.

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[37] A hard copy of the SDS is not required if an electronic version is accessible.
[38] Note that other spaces in schools may meet this definition as well, particularly art rooms and CVTE shops.

For purposes of school STEM programs, this includes the vast majority of chemicals typically used in schools, with the exception of very basic materials such as table salt, sugar, and baking soda. As noted previously, the OSHA Laboratory Standard is typically met when hazardous chemicals are used in science and technology/engineering spaces.

The 2016 Massachusetts Science and Technology/Engineering Curriculum Framework does not dictate the particular materials or activities that a STEM program must include, but does provide examples that inform such decisions. Two middle school standards for physical science standards suggest the use of particular chemicals (grade 6 and grade 8, respectively):

- 6.MS-PS1-6. … Examples of chemical reactions could include dissolving ammonium chloride or calcium chloride.
- 8.MS-PS1-2. … Examples of reactions could include burning sugar or steel wool, fat reacting with sodium hydroxide and mixing zinc with HCl (hydrogen chloride).

Each of these four chemicals is considered hazardous under the OSHA definition. Other chemical phenomena are commonly illustrated using vinegar (acetic acid – CH_3COOH) and baking soda (sodium bicarbonate – $NaHCO_3$). Acetic acid, at approximately 5% typical in vinegar, is considered hazardous under the OSHA definition.

During interviews with middle school science educators, some chemicals that are typically used in their districts include: ammonia, bleach, borax, vinegar (acetic acid), baking soda, rubbing alcohol, hydrogen peroxide, iodine, bromthymol blue, calcium chloride, citric acid, magnesium sulfate, and zinc. Given the classification of many of these chemicals as hazardous by the OSHA definition, even in diluted solutions and small amounts, and their typical use in science labs would mean the OSHA Laboratory Standard would apply.

Assumption of hazardous chemical use in elementary school curriculum

A goal of all schools should be to reduce the use of hazardous chemicals as much as possible.[39] Conducting a program without hazardous chemicals means the OSHA Hazard Communication and Laboratory standards do not apply, and there is no need for significant chemical safety systems. When a program can be conducted without hazardous chemicals, the school benefits through significantly lower costs of construction, operations, and maintenance, as well as reduction of in-class hazards and liability.

Elementary schools are the best candidate for conducting STEM programs without hazardous chemicals, and a goal of no hazardous chemicals is achievable in these grades. Result of a review of the grades Pre-K–5 STEM learning standards, educator focus groups, and input at state STEM conferences suggests that this is possible. Schools should formally adopt a position of reducing hazardous chemicals and make it explicit in school and/or district policy.

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[39] EPA: www.epa.gov/saferchoice; Mass.Gov: www.mass.gov/files/documents/2016/08/nt/schlchem.pdf; NSTA: static.nsta.org/pdfs/MinimumSafetyPracticesAndRegulations.pdf, www.nsta.org/about/positions/liability.aspx; ACS: www.acs.org/content/acs/en/greenchemistry.html?cid=home_trending

A key exception at elementary school is the very common use of vinegar (~5% acetic acid) which is classified as a hazardous chemical. Building significant chemical safety systems in elementary classrooms, however, is not realistic based on limited use of vinegar. If a school chooses to use a chemical like vinegar in limited instances, it is possible to do so from an operational perspective. The school will want to document the nature of the risk that is being taken, what the educational value is, what they have done to mitigate the risk (e.g., use of splash goggles, reduce the amount of vinegar available, contain the vinegar, have the teacher use the vinegar, etc), and procedures to follow in case anything happens. This approach can mitigate the risk while conducting the learning activity and ensure that if anything does happen appropriate actions can be taken.

<u>Recommendation for limiting hazardous chemicals in middle and high school</u>

The Global Harmonized System (GHS) categorizes chemicals through the use of two signal words, pictograms of hazard types, and a 1–4 scale for severity of the hazard. In the GHS 1–4 severity system, Category 1 chemicals are most dangerous.[40] The signal words are:

- *Danger*
    - Used for more severe hazards
    - E.g., hydrofluoric acid (HF), chlorine (Cl), 12 molar hydrochloric acid (HCl), lead nitrate ($Pb(NO_3)_2$), potassium iodine (IK)
- *Warning*
    - Used for less severe hazards
    - E.g., 6 molar hydrochloric acid (HCl), 0.1 molar hydrochloric acid (HCl), 5% acetic acid (vinegar)
- Any other chemicals are considered “Not classified”
    - E.g., sodium chloride (NaCl), potassium chloride (KCl) solution, chlorine water (though this is still Category 2 acute aquatic toxicity)

Based on input from professionals that have worked with the GHS system and with schools regarding chemical education, it is recommended that schools consider the following guidelines when choosing chemicals for their STEM program:

- Grades K–5: Prohibit use of chemicals with signal words Danger *and* Warning
- Grades 6–12: Prohibit use of chemicals with signal word Danger, and highly recommend avoiding chemicals with signal word Warning that are Category 1

<u>Strategies to reduce impact of hazardous chemicals when they are necessary</u>

An important strategy to reduce or avoid the use of hazardous chemicals is to identify alternative chemicals that are safer, healthier, and more sustainable, or to identify alternative activities that achieve the same learning goal with less hazardous chemicals. These are the goals of green chemistry, discussed next. Any chemical or mixture that has a “Danger” signal word should be carefully evaluated and when possible substituted. When hazardous chemicals need to be used, schools should aim to use as little as is necessary, including using dilute solutions when that can reduce the risk to students. In certain situations, it can be viable to use

[40] This is opposite of the NFPA system, discussed later.

microscale chemistry techniques as well. In visits and interviews conducted for this report, it is clear that Massachusetts schools are increasingly implementing these strategies.

Green chemistry approach
Green chemistry is about identifying safer, healthier, and more sustainable choices in materials use and learning activities. While the chemicals ultimately identified may still be hazardous by the OSHA definition, the goal is to make less hazardous choices.

Science administrators are also implementing microchemistry to assist with safety and budget considerations, consistent with green chemistry principles. Microchemistry is the practice of using very small volumes or masses to complete chemical reactions. This can be very beneficial when safety is a particular concern. Microchemistry does have some limitations in certain educational contexts (such as difficulty observing gas generation in a reaction) and may require equipment designed specifically for this approach. Those should be considered in light of the safety benefits.

Selected green chemistry resources are provided in the appendix.

Actively manage chemical hazards and maintain chemical safety systems
Schools should be proactive in managing hazardous chemicals and chemical safety systems, including:

- Provide proper storage, handling practices, and disposal options
    - A school owns all hazardous chemicals from cradle to grave, from ordering through the disposal
- Maintain SDS forms[41] for every chemical used in the lab, keep them visible and accessible
- Provide relevant and proactive training for teachers and supervisors (administrators, curriculum coordinators, or others)
- Establish a system such as a safety contract for students
- Test systems regularly
- Fix anything that is broken
- Ensure staff have keys to reset emergency gas shut offs
- Policies and practices for reducing hazardous chemicals in the STEM program
    - Aim for no hazardous chemicals first, then identify only what is needed
    - Purchase and use as little as possible and as dilute a solution as possible
    - Make neutralization part of regular lab procedure; if acids and bases are treated as part of regular lab practice and before it is considered waste, then the by-products are no longer hazardous (as long as the pH is between 2 and 12.5) and disposal is easier and more cost effective

[41] No longer use Material Safety Data Sheets (MSDS). The implementation of the Global Harmonized System (GHS) requires the use of the signal words, categories, and pictograms to communicate hazards. SDSs use the GHS system. Vendors provide an SDS with the delivery of every chemical.

- Ensure compliance with hazardous waste storage and disposal (including staff training) per Massachusetts and federal Hazardous Waste regulations

Planning for safe STEM instruction

Interviews with Massachusetts science educators during this review, and observations over time and locations around the state by the authors, indicate that few districts are providing regular and thorough safety information and training to educators and students necessary to ensure a safe STEM program. Additionally, a comprehensive view of science safety is not typically taught in Massachusetts teacher preparation programs. Safety problems in schools are often a result of a lack of safety policies, protocols, and best practice. Chemicals and other supplies are frequently improperly stored. Poor housekeeping methods are often observed, evaluation of supplies and equipment is often lacking, and slow responses to fix broken equipment are typical. Too frequently there is a lack of, or improper use of, personal protective equipment. Administrators, STEM teachers, and students must receive regular safety training relevant to their roles and duties, and schools should develop a culture of safety that includes regular implementation of best practices to engender a safe learning environment.

<u>Staff training is critical</u>

School or district safety plans, staff training on those plans and on specific safety systems, and training on how to design safe curriculum and conduct STEM activities safely are all critical elements to achieving a safe STEM program. Some plans and trainings are required by federal or state regulations (e.g., a Chemical Hygiene Plan based on OSHA's Laboratory Standard). A majority of the resources that address safety in the science lab contain procedures for training educators and students about safety. The American Chemical Society (ACS) and the National Science Teachers Association (NSTA) provide examples of Personal Protective Equipment Lists, Chemical Hygiene Plan, and Safety Training.[42] These and other resources are provided in the Appendix. Support for developing school-based safety plans and training programs are scattered and localized (e.g. some county extension offices may help a school plan for hazardous wastes, but not all), so it can be difficult for a school district to develop comprehensive plans. But schools must work toward this goal.

Further, the district and school should approach safety as a system responsibility. Consider the roles, responsibilities, and training of educators, the district or school Chemical Hygiene Officer, Nurse, administrators, Emergency Response Coordinator, Purchasing Office, and others that together contribute to a culture of safety and ensure implementation of best practices across the system.

<u>Instructional planning with safety in mind</u>

Safety must be a constant consideration in planning STEM learning activities as all STEM activities elicit some sort of risk. To mediate this, educators should consistently assess risks of each learning activity, actively reduce the risks as possible while still maintaining key learning

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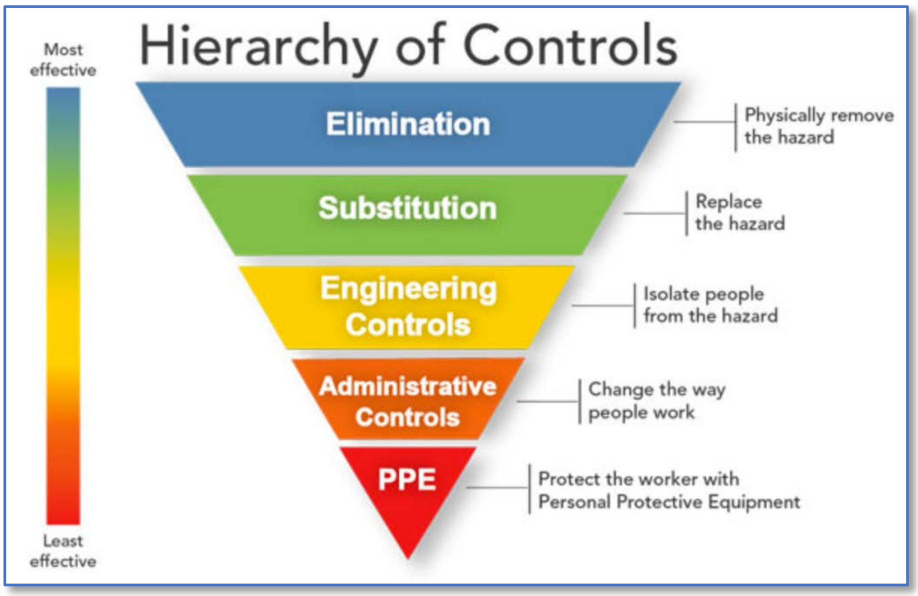
[42] ACS: www.acs.org/content/acs/en/education/policies/safety/chemical-health-and-safety.html; NSTA: www.nsta.org/safety/.

goals, and document steps taken and plans made.[43] Some key questions to consider and document can include:

- What are the risks and why are they necessary to achieve the learning goal?
- What has been done to reduce risk (hazard & exposure)?
- What harm could be incurred, and what do we do if something happens?

Appropriate and proper safety equipment and procedures must be in place for any given learning experience.

Looking beyond the individual curriculum activities, it is helpful to view the STEM program through the lens of the National Institute for Occupational Safety and Health's (NIOSH) Hierarchy of Controls.[44]



NIOSH Hierarchy of Controls.

STEM educators tend to think most frequently about personal protective equipment (PPE), as that is what students are most directly using during a learning activity. Administrative controls (such as how to move chemicals from a chemical storage room to a science lab) are also often considered, but given the wide variety of potential administrative controls that may be applied to particular processes, this can always be considered more comprehensively. STEM programs would be well served to give more attention to elimination and substitution options. These decisions have the greatest potential to enhance safety by removing certain risks entirely or substituting the nature of the risk with something less hazardous. For any given hazard there

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[43] Industry practice is to conduct a written risk assessment for all activities utilizing hazardous chemicals.
[44] Found at: www.cdc.gov/niosh/topics/hierarchy/default.html

are a variety of options available to reduce the risk to staff and students.[45] The two tables provided as a supplement to this report provide examples of common laboratory hazards and potential options by each level of control relevant to STEM learning spaces.

The discussion in this section highlights a few best practices to enhance safety in STEM programs. This section is not comprehensive. While this review is focused on STEM learning spaces, these also apply to other learning spaces such as art rooms.

Systems

This section touches on selected safety topics of relevance to building design that arose during interviews and discussions conducted throughout this review. The topics presented in this report are not comprehensive; see the two tables provided as a supplement to this report and resources provided in the Appendix for additional information.

System design and maintenance is essential

Safety systems are only good if they work as designed and for the purposes for which they were intended. Schools must understand what each system was designed for, and maintain the systems so they are available when needed. Schools must:

- Include proper placement of signage to identify safety equipment
- Keep safety systems clear of obstructions for quick accessibility
- Conduct regular maintenance or updates to ventilation systems, gas, and electric utilities
- Fix or replace anything that is broken, worn, or expired
- Develop safety plans in which the available systems are an integral, but not the only, component of conducting safe STEM education
- Provide all potential users of the systems with training

Systems for all STEM learning spaces

Personal Protective Equipment[46]

OSHA (1910.133) and state law (MA General Law [M.G.L.] c.71 §55C) requires eye and face protection from items found in any classroom such as flying particles, liquid chemicals, and chemical vapors.[47] Everyone, including students, teachers, and visitors, should wear properly fitted splash-proof safety goggles[48] when working or observing chemicals, hot liquids, or potential flying objects. While the American Chemical Society recommends that chemical splash goggles be stored in a UV-sanitizing goggle cabinet (ACS, 2012, p. 17),[49] it can be more effective

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[45] See NSTA's Safety and School Science Instruction position statement (2014) for additional suggestions and resources: www.nsta.org/about/positions/safety.aspx.

[46] Failure to provide students with PPE as written on an SDS is a violation of OSHA law.

[47] OSHA: www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.133; Massachusetts: malegislature.gov/Laws/GeneralLaws/PartI/TitleXII/Chapter71/Section55C

[48] Goggles should meet ANSI standard (Z87.1) for impact resistance.

[49] Also see ACS elementary recommendations, p. 20 for cleaning shared goggles recommendations: www.acs.org/content/dam/acsorg/about/governance/committees/chemicalsafety/safetypractices/safety-in-the-elementary-school-science-classroom.pdf.

for schools to provide personal goggles for every student to eliminate the need for sanitization. If included, a sanitizing cabinet should be large enough to hold goggles for two classes (as there is typically not enough time to run the sanitizer between class sections). Additionally, shared goggles should be thoroughly washed, including the straps, to prevent transmission of environmental microbial contamination. UV bulbs need to be replaced regularly to ensure their effectiveness.

Fire extinguishers

The use of Bunsen burners in high school are just one obvious source of fire in STEM learning spaces. Other sources can be found in these spaces at all grade levels, and will continue to diversify as schools increase offerings in robotics, electronics, and digital tools. Potential heat or fire sources may include solder irons, battery packs, hot plates, heat presses, electronic circuitry, or a variety of other electrical appliances or tools.

Appropriate fire extinguishers should be found in every educational space (per National Fire Protection Association [NFPA] Table 13.6.2) near the escape route; the type should match the expected use per NFPA 10, sec 13.6.1.1.[50] Placement of the fire extinguisher near the exit should allow for somebody in the hallway to basically reach in through the door to grab it. This means that placement must be on the latch side of the door, opposite the hinge side, 2–4 feet from the door. Mis-placement is very common. An extinguisher should be placed in each chemical storage area, and ideally prep room where chemicals are stored or used as well, so no staff member has to leave the room to get an extinguisher. Employees must be trained on the use of the extinguishers.

Fire Blankets

A fire blanket is not required in general classrooms or in labs where there is also a deluge shower (MA 527 Code of Massachusetts Regulations [CMR] 1.00, sections 10.23 through 10.23.4.3.1). [51] NPFA 45 (A.6.5.3.2 and the appendix) advocates a stop, drop, and roll approach over fire blankets in labs; the use of the deluge shower is an option when immediately at hand. Some STEM labs, particularly technology/engineering labs (including makerspaces) may require a fire blanket given the likelihood of heat sources (such as soldering irons) and the lack of a deluge shower.[52] When present, staff must be trained on the proper use of fire blankets.

Eyewash Stations

Eyewash stations are a definite recommendation for STEM rooms because of the sensitivity of the eyes. Vapors, liquids, dust, or other irritant can be prevalent in labs, making eyewash stations a critical tool to address any incidents involving the eyes. Eyewash stations are required by OSHA and Massachusetts fire code. In accordance with the American National Standard Institute (ANSI) Z358.1-2014,[53] eyewashes are required to deliver tepid flushing fluid

[50] Consult local fire safety officials as many variables determine the fire safety systems needed in a space.
[51] Consult local fire safety officials as many variables determine the fire safety systems needed in a space.
[52] Consult local fire safety officials as many variables determine the fire safety systems needed in a space.
[53] As well as 2015 International Building Code (IBC) and International Plumbing Code (IPC) Section 411.1 and 411.2.

(60-100 degrees Fahrenheit). This implies a plumbed-in eyewash station to maintain this temperature, although faucet-mounted eyewashes are viable where a plumbed-in option is not possible. A faucet mounted eyewash station requires turning the hot water lever and the cold water lever and then pulling a center lever. That said, it is more important from a practical perspective to have an eyewash available, even if it is mounted on a faucet, than to not have an eyewash available due to lack of direct plumbing. Portable eyewash stations have the risk of possible bacterial contamination and they do not supply a sufficient amount of water to flush the eyes for the recommended 15 minutes; these should not be allowed.

One eyewash per classroom is sufficient, although the Designer should consider maximum distance requirements from ANSI Z358.1-2014. There is no harm in having an additional eyewash station placed on opposite sides of a room for rapid access from anywhere in the room, but this is not a requirement. Keep areas around the eyewash station clear to provide easy access in case of an emergency. In addition to science labs, eyewashes should be provided in elementary science and technology/engineering rooms and technology/engineering labs.

In regards to maintenance, ANSI Z358.1-2014 requires flushing equipment weekly to clearing the plumbing of any deposits and prevent bacterial growth. Annual inspections should be completed to determine whether the eyewash stations continue to meet requirements.

Natural gas

The availability of natural gas (gas jets) is not necessary in elementary or middle school to meet state learning standards for those grade spans. Hot plates are an acceptable heat source for activities employed to demonstrate the core ideas in the standards. No gas is needed in a technology/engineering lab (e.g., tech ed room, makerspace) at any grade level.

At high school, natural gas is typically used in chemistry-related classes. When Bunsen burners are used, it is best practice to provide an identified area on the lab bench for where it is safe to place the burners (e.g., back from the edge, not under cabinets). Use yellow caution tape on the lab bench to designate these areas.

Gas jets in science labs are frequently observed to be broken or jammed, resulting in systems that have been shut off entirely due to concerns about safety. When included in a high school lab, gas jets should be regularly maintained and evaluated, with an operable safety shut off near the exit door, that requires a key to reset.

Broken glass

Include a separate, clearly marked container to place any broken glass (e.g., beakers, glass cabinet doors). Broken glass should not be disposed of in the regular trash as custodial other staff may inadvertently cut themselves when handling the bags.

Electrical circuits

All electrical outlets subject to moisture need to be protected by ground-fault circuit interrupters (GFCI), subject to compliance with MA 527 CMR and NFPA-70.

These are only a representative list of systems that are particularly salient based on this review. Additional aspects of these systems or other safety systems may also need to be considered for a particular STEM space.

Anytime large or benchtop electromechanical machines are used, the room should include emergency stops that will shut off power to all electrical circuits except the room lights. These emergency stops must allow for the power to be shut off from anywhere in the room within 10 seconds, which may require multiple stops in a particular room.

Systems for safe use of hazardous chemicals

Chemical Storage

Many safety problems in schools are a result of a lack of safety protocols, including how chemical supplies are stored. Schools should review all chemicals used, not just those used in typical chemistry classes, such as glues, solvents, or finishes (e.g., spray paints). A dedicated chemical storage room should be provided anytime hazardous chemicals will be stored for longer than is needed for short-term use. The following are some best practice recommendations for chemical storage rooms; this list is not comprehensive but highlights key points that commonly arise. See additional resources provided in the appendix, particularly *Prudent Practices in the Laboratory* (NRC, 2011). In particular the following emerged during this review:

- Provide dedicated ventilation for the chemical storage room
    - Chemical storage cabinets do not require ventilation[54]
- Include flammables cabinet when flammables are used or anticipated
- Chemical storage cabinets should be a maximum size of 4 ft x 4 ft, with self-closing double doors
    - Schools should not have more chemicals that need to be stored than these cabinets will hold
    - Good inventory control is required to maintain these levels[55]
    - Keep in mind that nitric acid (which should be avoided) needs a separate storage even from other acids
    - One shelf of each cabinet may be designated for holding waste materials
- Include a plumbed-in eyewash station
- An appropriate fire extinguisher is required[56]
- Doors leading into prep rooms and chemical storage areas in which chemicals are stored must have a storeroom lock (outside lever fixed, entrance with a key only; inside lever always unlocked for immediate exit) and have a self-closing device

[54] Consult local fire safety authorities or building code. There are limited instances where ventilation of a cabinet is required based on the nature of a particular chemical being stored; those types of chemicals, however, are not typical and should not be present in schools.

[55] See discussion above in the policy section about the value of a just-in-time purchasing approach.

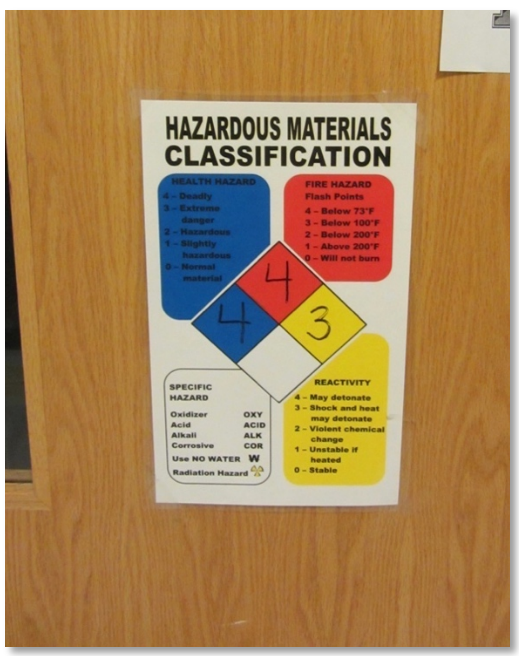
[56] Consult local fire safety officials as many variables determine the fire safety systems needed in a space.

- All doors leading to chemical storage (doors between hallway and chemical storage, including lab doors if that is the path to the storage) have to be marked with minimum 6” by 6” diamond placard (see fire graphics section below); these can be blank placards that are grease-pencil labeled or color photocopied with mylar covering.
- Consider the addition of an “in-use” light signal outside of the chemical storage room that turns on with the interior light to indicate that someone is inside.

<u>Fire graphics system</u>

The National Fire Protection Association (NFPA) provides a graphics system used by emergency personnel to identify risks posed by the presence of hazardous materials in a certain area (NFPA 704). Appropriate signage using the NFPA placard, below, should be included on all doors leading to areas where chemicals are stored, including any doors between the hallway and the chemical storage room (even when that requires passes through a prep room) and any classroom where chemicals are actively being used.

While state fire code relies on the NFPA system for emergency signage, SDSs and school chemical management systems use the Global Harmonized System (GHS). Each system has a unique purpose so schools need to work with both; NFPA and OSHA provide information on the relationship between these systems and how to work across the two.[57]



Signage on door to school chemical storage room.

[57] A quick card with this information can be found at: www.nfpa.org/Assets/files/AboutTheCodes/704/NFPA704_HC2012_QCard.pdf.

Hazardous waste storage and disposal

The use of hazardous chemicals in schools means that hazardous waste will be generated, particularly in high schools. All hazardous waste must be stored and disposed of properly (see MA Department of Environmental Protection [DEP] 310 CMR 30.000, and Resource Conservation and Recovery Act [RCRA] CFR 40 parts 239–282); none can be put down the drain (MA Plumbing Code 248 CMR 10.00 / Section 10.13)[58]. As discussed in the policy section above, schools should aim to order, use, and store as little chemicals as possible, and choose safer, healthier, and more sustainable options. Given that some hazardous chemicals will be in the lab, appropriate waste management and disposal has to be planned for and implemented. Schools typically produce low quantities of hazardous waste so can be considered a Very Small Generator of Hazardous Waste, a MA DEP designation that encourages schools to "minimize the amount of hazardous waste you produce (and take advantage of the flexible requirements for "Very Small Quantity Generators") by substituting non-hazardous products for hazardous ones, by reusing or recycling hazardous wastes wherever possible, and by not mixing non-hazardous with hazardous wastes" (MA School Chemical Management Program[59], p. 111).

School must ensure that basic requirement for a hazardous waste storage area are met, including proper signage, limited access, secured and closed containers, separation by compatibility, proper placement (e.g., not on top of wall cabinets), spillage containment, and lighting. All relevant staff should be trained and maintain dated inspection records.

Acid Neutralization

An acid neutralization system is only necessary for, and only effective on, mineral acids[60], and only required if the pH of those acids are 2 or less. While mineral acids are commonly used in schools, they are just one category of chemicals used, and few schools use much acid of this strength. Schools typically do not generate large enough amounts of mineral acid waste to justify the expense of a large neutralization system, and if neutralization is made a regular practice in lab procedures, all caustic waste (with pH of 2 or less or 12.5 or more)[61] can be eliminated.

Additionally, while many schools have acid neutralization systems, or even acid/base neutralization systems (which can effectively address bases with pH more than 12.5), these are very frequently misused. Much too often these systems are viewed as, and used as, the overall waste disposal system. These systems do not do anything to treat or remediate other hazardous chemicals poured into the system, so functionally any other hazardous chemicals just get held in the tank for a period of time with a great chance of additional hazardous by-

[58] The MA Plumbing Code 248 CMR 10.00 Section 10.13 is clear that hazardous wastes have to be treated before being discharged into a sanitary system: www.mass.gov/files/documents/2017/09/28/248cmr10_0.pdf

[59] Found at: www.mass.gov/files/documents/2016/08/nt/schlchem.pdf

[60] Not including Nitric Acid which converts to nitrate salts, an oxidizer, that cannot be disposed down any drain.

[61] Aqueous wastes with a pH greater than or equal to 12.5, or less than or equal to 2 are corrosive under Environmental Protection Agency (EPA) Hazardous Waste Identification Regulations. A waste may also be corrosive if it has the ability to corrode steel in a specific EPA-approved test protocol.

products created (creating new hazards), and ultimately those all get passed through to the municipal system anyway (in violation of code). So it is best to neutralize mineral acids as part of the regular lab procedure and deal with them before any consideration of disposal, and treat all other hazardous waste appropriate to the particular chemical being disposed of (not down the drain in any case – see previous section).

The inclusion of acid neutralization is problematic because:

- The amount of acid typically used and disposed of is small (and can be zero if following best practice of neutralization as part of lab procedure) and disproportionate to cost of a large neutralization system
- The systems give people the false sense that they can pour anything down the drain, which they cannot but often do
- It represents an unreasonable risk to people when the system fails or it is misused (e.g., nitric acid is poured into the system generating toxic gas which can make its way out of the system)
- It requires a monitoring system, which requires frequent maintenance and often fails
- Other activities, including regular handwashing with soap, can interfere with the effectiveness of the system

If a school deems it necessary to include an acid neutralization system, they must commit to use it appropriately, train everyone on its use (staff and students), and maintain it over its full life. Additionally, the system must be designed in compliance with MA Plumbing Code 248 CMR 10.00 Section 10.13, regarding piping and treatment of special hazardous wastes. Such a system is only required if schools will be pouring corrosive, very acidic mineral acids down the sink. All sinks that drain to the acid neutralization system should be labeled as such so that they are not used for other activity that may interfere or hinder the effectiveness of the system. District staff and the design team must work together to determine what corrosive chemicals are anticipated, and provide appropriate plumbing treatment systems and operational procedures accordingly.

<u>Deluge Showers</u>

Deluge showers are an important element of any response to accidents involving hazardous chemicals. The 2015 International Building Code (IBC) and International Plumbing Code (IPC) Section 411.1 and 411.2, and compliance with ANSI Z358.1-2014, states that there should be one shower per lab, located within 50 feet of where chemicals are stored or used, with a sign "Emergency Shower." Showers are only needed, however, in situations where hazardous chemicals are in use and the OSHA Lab Standard (1910.1450) applies. This likely applies to all science laboratories and may apply to technology/engineering labs where chemicals are used (see policy discussion above).

The effective best practice recommendation is to *not* include a drain.[62] A drain should not be included unless the school has a sufficiently sized holding tank (which most do not, and should

[62] IPC 411.2 notes that a drain is not required.

not), and a trap primer at each station would be required. Additionally, a holding tank would require a distinct drainage system from an acid neutralization system (which most do not need either, see previous section). During an emergency, the water resulting from using the shower must be treated as hazardous waste given that the use of the shower would be triggered by the need to remove hazardous chemicals on a person (unless the particular chemical is rendered non-hazardous through significant dilution). This contaminated water cannot be put down a regular drain and clean-up should reflect the chemical(s) involved. Unless the chemical happened to be a mineral acid, sending that contaminated water through an acid neutralization system does not treat the hazard. So if a drain were to be included, it would need to drain to a large holding tank, and all water collected in that tank (even if just from regular testing of the showers) would need to be disposed of as hazardous waste.

Without a drain, recognize that the volume of water produced when using the shower in an emergency situation is significant, and the implications of that much water on the floor need to be accounted for. During design, surrounding areas should be assessed, including any cabinetry, and an assessment made of where the water is likely to go (including any potential of the water finding its way through the floor to any spaces below). When a deluge shower is included, it should be visually inspected weekly and tested/flushed every six months (per MA 527 CMR 10.24.3.1). During testing, the release of water can be anticipated and an appropriate tub or alternative can be employed to capture and drain the clean water to a sink during testing.

The area under the shower and approaches to the shower must be maintained for clear passage and use, and be accessible to the handicapped (refer to ANSI Z358.1-2014 for minimum dimensional requirements). Mark off an area around the shower with yellow caution tape on the floor to designate that no other objects or materials should be kept in this zone.

Access to deluge showers and eyewashes: clear access (left) and obstructed (right).[63]

[63] Note that both images show drains which are not recommended.

Fume Hoods

Fume hoods are required in science laboratories where flammable and other hazardous chemicals are used (NFPA 45, NFPA 30). The NSTA recommends that all labs should provide fume hoods and ventilation systems. There are many chemicals that may be used in a science lab that can produce hazardous fumes. The NSTA Minimum Safety Practices and Regulations: January 2017 states that a fume hood is particularly necessary if using nitrogen dioxide, sulfur dioxide, or hydrogen sulfide.

The middle school science curriculum does not require the use of particularly hazardous chemicals, and most if any chemicals used at this grade span will not require a fume hood. The Focus Group of middle school science educators that were interviewed for this review, as well as additional interviews with teachers at site visits, stated that if they did have a fume hood in the lab or the prep room, they were not used for their intended purpose of ventilating harmful chemicals. In referencing the chemical list generated from interviews of the materials used and needed to perform experiments, the low concentrations and small quantities of chemicals used do not require the use of fume hoods. For middle school, there likely is a need to provide at least one fume hood associated with the chemical storage room to allow for appropriate handling and preparation of solutions in that location, but not in individual science labs.

Any double-sided fume hoods placed between a science lab and prep area need to provide for locking at least one side (preferably the prep room side) of the hood. This is to maintain security of the prep room; without the lock somebody can climb through the hood to access the prep room.

Negative room pressure

In the rare instances where significant fumes are released into a science lab, a system that maintains negative room pressure relative to the rest of the school acts to contain the fumes in the science lab. Other by-products of STEM or project-based activities (e.g., dissection in Biology classes) can also produce a smell that the school does not want to have spread beyond the science lab.

During this review several labs were observed that additionally had a whole-room exhaust or air purge system. While anecdotally this was useful in very specific situations where the air in the room could become uncomfortable (such as with the smell of a class dissection in a biology course), these situations were extremely rare, should be mediated in the first place, and if such conditions develop should trigger evacuation of students from the room (rather than purging the smell and carrying on). There are very few situations where the volume or concentration of chemicals used should trigger the need for a system beyond the negative room pressure and regular ventilation, as well as direct exhaust provided by a fume hood if available.

STEM design in context

STEM education is a critical element of every school program, and increasingly is a focus of public education in Massachusetts. Given district flexibility in the design and implementation of academic programming in Massachusetts, there is no standard design for curriculum, safety systems, or school design that will work for all. This means that school staff and building designers must closely collaborate to identify the range of STEM activities, equipment, chemicals, materials, and systems that are likely to be used in a particular space. A quality STEM program will employ a variety of strategies and experiences, and hence a variety of activities, that requires flexible use of STEM spaces across school year and over time. A successful K–12 STEM education program prepares every student for success in an increasingly technical society and workplace, where they can contribute to a literate society, an economically viable workforce, and our global ability to address grand challenges.

Every STEM program must carefully attend to student safety to support engaging and active learning. Beyond the policy and cultural context of a school, safety procedures and systems are critical to quality STEM programs. STEM staff must be supported by the school and district to ensure that safety is considered and implemented as a coherent system. Staff and student training are critical to ensuring that safety is attended to and implemented as intended. Schools and districts must commit to the ongoing professional development of staff, and maintenance of equipment and systems, to be able to implement and maintain a quality STEM program. The appropriate design and use of STEM spaces is only possible when contextualized as an integral element of the school and district’s programming and procedures. A well-designed educational program provides each and every student the opportunity to achieve STEM learning standards and succeed after high school.

Appendices

Selected references and resources

STEM education program and space planning

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Web resources

Massachusetts Technology Collaborative, Index of the Massachusetts Innovation Economy: www.masstech/org/index
National Association for the Education of Young Children: www.naeyc.org/resources/position-statements
National Association of Early Childhood Specialists in State Departments of Education: www.naecs-sde.org/

Makerspaces and making education

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Roy, K.R., and Love, T.S. 2017. *Safer Makerspaces, Fab Labs, and STEM Labs: A Collaborative Guide!* National Safety Consultants, LLC (Available from www.iteea.org)

Web resources

Agency by Design (Harvard Project Zero): http://agencybydesign.org/
Boston Maker Educators: www.bostonmakereducators.org/k12-boston-makerspaces.html
Community Engineering Portable Studio: www.communityengineering.org/portablestudio/
Engineering Learning Systems, Tufts CEEO: www.communityengineering.org/
Fab Foundation: www.fabfoundation.org/
Invent to Learn (book) resource links: https://inventtolearn.com/resources/

Learning in the Making: A Comparative Case Study of Three Makerspaces: www.hepgjournals.org/doi/abs/10.17763/haer.84.4.brr34733723j648u?code=hepg-site
Link Engineering: www.linkengineering.org/
MakerEd: https://makered.org/

- Makerspace Playbook: makered.org/wp-content/uploads/2014/09/Makerspace-Playbook-Feb-2013.pdf

MakeShop Learning Practices (Pittsburg Children's Museum): link on Makerspace for Education: www.makerspaceforeducation.com/
Making + Learning: makingandlearning.squarespace.com/
MIT Edgerton Center: Makerspace Resources for K–12 Educators: http://k12maker.mit.edu/
MIT Fab Lab FabCentral: http://fab.cba.mit.edu/
Massachusetts K–12 Engineering: www.engineeringk12mass.org/
SCOPES Digital Fabrication, Community of Practice: www.scopesdf.org/
STEAM Studio Curriculum: http://steamcurriculum.weebly.com/media.html

Green chemistry

Web resources

Beyond Benign (green chemistry curriculum): www.beyondbenign.org/curriculum/
EPA Green Chemistry: www.epa.gov/greenchemistry
EPA Healthy Schools, Healthy Kids: www.epa.gov/schools
MIT Green Chemistry Alternative Wizard: ehs.mit.edu/site/environmental-stewardship/green-chemistry
Massachusetts Toxic Use Reduction Institute at UMass Lowell: www.turi.org/
My Green Lab: www.mygreenlab.org/
Rehab the Lab (green chemistry alternatives): www.hazwastehelp.org/educators/rehabthelab.aspx; www.hazwastehelp.org/educators/index.aspx

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Web resources

3D Printing: What's the Harm?:
www.researchgate.net/publication/308023202_3D_printing_What%27s_the_harm

American Chemical Society

- www.acs.org/content/acs/en/education/policies/safety/chemical-health-and-safety.html
- www.acs.org/content/dam/acsorg/about/governance/committees/chemicalsafety/publications/acs-secondary-safety-guidelines.pdf
- www.acs.org/content/dam/acsorg/about/governance/committees/chemicalsafety/publications/chemical-safety-manual-teachers.pdf
- www.acs.org/content/dam/acsorg/about/governance/committees/chemicalsafety/publications/reducing-risks-to-students-and-educators-from-hazardous-chemicals.pdf
- www.acs.org/content/dam/acsorg/about/governance/committees/chemicalsafety/safetypractices/safety-in-the-elementary-school-science-classroom.pdf
- www.acs.org/content/acs/en/greenchemistry.html?cid=home_trending

American National Standards Institute: blog.ansi.org/2018/07/emergency-eyewash-station-shower-ansi-z358-1/

Board of State Examiners of Plumbers and Gas Fitters:
www.mass.gov/files/documents/2017/09/28/248cmr10_0.pdf

Boston University Research Support: www.bu.edu/researchsupport/compliance/laboratory-safety/

Council of State Science Supervisors: http://www.csss-science.org/recommendations.shtml

Centers for Disease Control and Prevention (CDC), National Institute for Occupational Safety and Health (NIOSH): https://www.cdc.gov/niosh/docs/2007-107/pdfs/2007-107.pdf

Environmental Protection Agency:

- Chemical Management Resource Guide for School Administrators: www.epa.gov/sites/production/files/2017-01/documents/chemical_management_resource_guide_school_administrators_508.pdf
- Safer Choice: www.epa.gov/saferchoice

ITEEA

- Safety Resources: www.iteea.org/Resources/Safety/Safety_Tests.htm; www.iteea.org/Resources/Safety/Additional_Resources.htm
- Safer Tool Use in Elementary Schools: www.iteea.org/File.aspx?id=107093&v=3b7fe097
- www.iteea.org/STEMCenter.aspx

Laboratory Safety Institute: www.labsafety.org/resource

Massachusetts Department of Public Health. Chemical Storage in Schools:
www.mass.gov/eohhs/gov/departments/dph/programs/environmental-health/exposure-topics/iaq/pollution/chem-storage/chemical-storage-in-schools-and-impact-on-iaq.html

Massachusetts Executive Office of Labor and Workforce Development, Department of Labor Standards Checklist for Schools: www.mass.gov/files/documents/2017/11/24/self-audit-safety-checklist-for-school-classrooms.pdf

Mass.Gov

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- www.mass.gov/service-details/occupational-safety-and-health-program-information
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National Fire Protection Agency: www.nfpa.org/

National Science Teachers Association

- www.nsta.org/safety/
- static.nsta.org/extras/riseandshine/Appendix5.1.pdf
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- nstacommunities.org/blog/2018/08/23/chemical-safety-training-for-science-teachers/

Occupational Safety and Health Administration

- www.osha.gov/law-regs.html
- www.osha.gov/laws-regs/standardinterpretations/2009-06-01
- www.osha.gov/dte/grant_materials/fy09/sh-18796-09/hazardcommunication.pdf
- www.osha.gov/Publications/laboratory/OSHAfactsheet-laboratory-safety-chemical-hygiene-plan.pdf
- www.osha.gov/Publications/laboratory/OSHA3404laboratory-safety-guidance.pdf

Methodology

Process and key activities

Outcome

- Agreed upon methodology for initial phase of the Review and Analysis of current Massachusetts, National and MSBA Standards and/or Recommended Practices for providing Science and Technology/Engineering Education in K–12 Schools

Proposed methodology

The following tasks and activities are proposed to complete this first phase of the review:

i. Research and document best practices for science and engineering spaces (see draft list in the appendix for potential individuals, organizations, and references):
    a. Research and compile source documents and references
    b. Consult position statements and recommendations from relevant organizations, including NSTA, NEASC, NAEYC, ITEEA, and others
    c. Review current MSBA guidelines, relevant state safety and building codes, and OSHA regulations and policies (e.g., space per student; exits; water in classroom; safe movement of students; disposal of chemicals likely used in science instruction)
    d. Visit selected schools and classrooms to observe designs of general classroom, science, and engineering (e.g., makerspaces; design labs; fab labs) spaces used for STEM and project-based instruction
    e. Interview selected elementary and middle school faculty, curriculum specialists, safety specialists, MSBA staff, and others as relevant
        i. See attached draft interview framework

ii. Synthesize documentation to draft initial findings
    a. Draft summary considerations for different elementary program models:
        i. Since many elementary teachers teach all subjects, consider classroom needs to support a project-based approach to curriculum across subjects
        ii. Some elementary schools, however, have a science specialist, so consider physical space design of a separate science classroom
    b. For middle school, how might the MSBA guidelines for high schools be different when applied to middle school?
    c. More schools are including engineering spaces, either as a separate room (e.g., maker space) or in a library or other public space. Articulate a spectrum of possible program models and corresponding design considerations
    d. Draft initial findings related to additional specific design issues raised at the kick-off meeting, such as:
        i. Emergency shut off valve location (height, placement)
        ii. What equipment needs direct ventilation?
        iii. If have a shower, do you put a floor drain in?
            1. Cost of installation
            2. Cost of maintenance
            3. Frequency and procedure for testing
            4. Where does the waste go if using in emergency situation?

        iv. Microchemistry (and implications)
        v. Acid neutralization
            1. HS large tank vs. MS localized storage (e.g., under sink)
        vi. Fire blankets – appropriate to keep in specs? (about training)
    e. Confer with MSBA staff as needed to agree on appropriate level of specificity for particular issues, prioritization of topics, and framing of initial findings and recommendations.

iii. Finalize initial recommendations for best practice related to the components listed in the previous section.
    a. Suggestions to include quantities and sizing, configuration, outfitting, management, and maintenance related to:
        i. design of physical space
        ii. equipment
        iii. supporting technology
    b. Obtain informal feedback from select organizations to get input validity and scope of draft initial recommendations
    c. Deliverable: draft results and recommendations of the initial phase of the Review and Analysis of current Massachusetts, National and MSBA Standards and/or Recommended Practices for providing Science and Technology/Engineering Education in K–12 Schools. The draft will include:
        i. a narrative of the procedures used to date to conduct the Review and Analysis
        ii. initial findings based upon that Review and Analysis
        iii. initial recommendations for and draft list of "Best Practices" for the quantifying and sizing, configuration, outfitting, management, maintenance and use of educational space
        iv. references and resources

iv. Attend and lead a Charrette with the MSBA and the Facilities Assessment Subcommittee of the MSBA Board of Directors to discuss and establish the Form and Content of a Draft Report of the Review and Analysis

<u>Notes</u>

Additional site visits, interviews, and research to be conducted following the delivery of the initial draft, as identified and requested based on discussions and explorations with MSBA staff, as well as FAS and Board members.

Scope limitations:

- Not including traditional 'shop' spaces (e.g., wood shop, metal shop)
- Not including CVTE spaces
- Not including outdoor STEM learning spaces at this time

Interview and site visit framework

Note context and purpose of this review (established in initial outreach via email or call). Input will be synthesized with other interviews and resources and to develop recommendations for the MSBA to inform school design in the state. We will be synthesizing information from multiple interview and sources. We may, however, ask to reference your program if it serves as an illustration of best practices or space design that others should look to.

[NOTE: this framework includes too much for any one interview or site visit of an hour or two in length; the interviewer will choose particular program models and/or considerations based on the expertise and context of the person being interviewed and adjust as the conversation progresses. Interviewers will ensure that each point is addressed by several sources across the full set of interviews and site visits.]

<u>Range of possible elements to consider in interviews and visits</u>

There are several models for STEM programs – with corresponding space types – that we are considering. We will be considering both design, operational, and program considerations in each model. We are also likely to identify best practices and specifications that vary by grade level or span.

[Interview protocol: for each model below, review relevant questions from the second list; return to the next model here, cycle through second list again; and so on…adjust as needed for redundancy and overlap.]

Potential/common STEM program models:

1. Elementary classrooms where teachers teach all subjects, consider classroom needs to support a project-based approach to curriculum across subjects
2. Elementary science specialist with their own science room
3. Middle school science rooms/labs
4. STEM rooms/maker spaces/fab labs/project rooms (may look different by grade level/spans)
5. School "learning commons" (e.g., library-based project space) (any/all/different grade spans)
6. (Art spaces [if time])
7. (Outdoor spaces [if time])

Considerations for each program model above:

- Any best practices or special considerations for program, curriculum, or instruction when providing STE education in this model?
    - Including relationship to other school or program components
- Suggestions for sizing, configuration, outfitting, management, and maintenance of space and equipment in this model?
    - Specifications for overall space

        - Middle school and elementary space guidelines (overall or sq ft per student)? For HS science labs we assume 1440 sq ft space (60 sq ft for 24 students)
        - # of science labs, maker spaces, etc in a school? (by grade span, per # of students)
        - Appropriateness of the model for grade levels/spans?
        - Teacher ownership (need an assigned teacher/ok to share among a team, who manages and takes responsibility for the space)?
        - Storage recommendations? (amount, type, projects visible vs. hidden)
        - Recommended equipment lists? (assume equipment can be changed over time)
        - Space needs or physical considerations for particular equipment? (e.g., direct ventilation, gas or compressed air)
        - Any templates or good examples of effective layouts/designs?
        - Particular safety considerations?
        - Any best practices and/or references for the management and maintenance of space in the context of this model?
    - Technology needs for model, e.g.:
        - LCD projector location(s)
        - Probes, or connecting computers to equipment
        - Bandwidth for internet, teleconference, future VR use
- Any local, state, or OSHA safety and building codes, regulations, or policies that need to be accounted for (including codes for handicap access)?
    - e.g., space per student; exits; water in classroom; safe movement of students; disposal of chemicals

<u>Specific issues</u>

There are a number of specific issues that you may be able to help us think through.

- Do middle schools need gas (based on standards/curriculum)?
- Emergency shut off valve location (height, placement) – water and gas both?
- If have a shower, do you put a floor drain in?
    - Cost of installation
    - Cost of maintenance
    - Frequency and procedure for testing
    - Where does the waste go if using for real?
- What kinds of chemicals do middle schools use? Any that need special storage for hazardous chemicals?
- Microchemistry (and implications for space, storage, and safety)
- Acid neutralization
    - HS large tank vs. MS localized storage (e.g., under sink)?
- Fire blankets – appropriate to keep in specs? (about training)
- Height specifications for tables and counters (36” standard; 28”-34” standard for handicap; but may need adjustments for younger/smaller students)

- Greenhouses vs. shelves in windows

Additional references and resources
Thank you for your input.

- Ok to cite you or your organization as a source for particular resources or information you have provided?
- Ok to return with follow up questions if needed?

Any additional resources we should consider?

- Other people we should talk to?
- Schools we should visit to observe designs of general classroom, science, and engineering spaces used for STEM and project-based instruction?
- Useful articles, books, or documents we should check out?
- Organizations we should contact, talk to, or check out?

Schools and programs visited
A variety of schools and STEM programs have been visited throughout this review:

- Acera School, Winchester (private) (www.aceraschool.org/)
    - K–8 STEAM program with a focus on science, creativity, and leadership
- Bourne High School Innovation Studio (www.bourneps.org/Content/90)
    - Makerspace in converted woodshop for district-wide use
    - Serves all grades and subjects across the district
- Burlington Science Center (bsciencecenter.wordpress.com/)
    - Serves the district's elementary schools, also live animal program
- Burlington Marshall Simonds Middle School (www.burlington.org/departments/schools/marshall_simonds_middle_school/)
    - Middle school science labs designed by past district science director
- Cambridge College (elementary teacher education science lab)
    - Recent labs for elementary science teacher preparation (in old Hood facility)
- Cambridge Friends School (private) (www.cfsmass.org/CFSMakerSpace)
    - One of the first elementary maker spaces to be incorporated into a school's curriculum
- Franklin High School (www.franklinps.net/fhs)
    - Built about 5 years ago, used 2011 MSBA lab guidelines
- Gloucester High School (ghs.gloucesterschools.com/home)
    - Project-based work (e.g., designing instruments) and some integration across program (e.g., with physics)
- Haverhill Hunking K–8 School (hunking.haverhill-ps.org/)
    - Recently completed project that includes STEM project rooms adjacent to science labs for each grade level
- MIT Edgerton Center (k12maker.mit.edu/)
    - Focused on makerspace development and support
- Newton Zervas Elementary School (www.newton.k12.ma.us/Page/2318)
    - Recently constructed elementary school

- NuVu, Cambridge (private program, 9–12) (cambridge.nuvustudio.com/)
    - Pedagogy based on the architectural studio model and geared around multi-disciplinary, collaborative STEM projects
- Plymouth North and Plymouth South High Schools (www.plymouth.k12.ma.us)
    - Comparative set where PNHS was built about 6 years ago and PSHS just finished, allowed for comparison of science lab designs.
- Scituate Gates Middle School (www.scituate.k12.ma.us/index.php/gates)
    - A newly constructed middle school, focused on project-based learning
- Shady Hill School, Cambridge (private K–8) (www.shs.org)
    - HUB Center Makerspace - a dedicated maker space in STEM building with science labs
- Somerset Berkley High School (somersetberkley.org/)
    - Built about 4 years ago, used 2011 MSBA labs guidelines
- Springfield Central High School (central.springfieldpublicschools.com/)
    - Recent renovation with new and renovated science labs based on 2011 MSBA guidelines
- Tufts University Center for Engineering Education and Outreach (ceeo.tufts.edu/)
    - Resource development and program support for engineering education
- Tufts University Eliot-Pearson Makerspace (sites.tufts.edu/devtech/research-2/makerspace/)
    - A makerspace designed for early childhood programming
- Watertown High School (sites.google.com/a/watertown.k12.ma.us/fablab/)
    - A high school Fab Lab, housed in the school library
- Watertown Middle School (sites.google.com/watertown.k12.ma.us/wmsmaker/)
    - A library makerspace which serves the students, teachers and school community
- Watertown Public Library – HATCH Makerspace (www.watertownlib.org/hatch)
    - Makerspace affiliated with town library, but housed in a separate location

Organizations and individuals interviewed

Beyond the schools and programs visited above, the following individuals and organizations were additionally interviewed for this review:

- BettyAnn Howson, American Chemical Society
- Beyond Benign
- Dwight Peavey, Brandeis University, retired from EPA
- Hilary Hackbart, Massachusetts Department of Labor Standards
- Laboratory Safety Institute
- Massachusetts Department of Elementary and Secondary Education
    - Career and Technical Education Office
    - STEM Office
- Massachusetts Department of Fire Safety, Code and Compliance Office

Summary of input provided at conference sessions

Draft findings and recommendations from this review were presented at four events across Massachusetts to solicit input from a variety of stakeholders and better understand potential implications of the report. The four events included:

- MSBA Designer Roundtable, October 23, 2018
- Massachusetts Association of Science Teachers Conference, October 26, 2018
- Massachusetts Science Education Leadership Association Conference, November 1, 2018
- MA STEM Summit, November 14, 2018

A summary of input provided across the four events is provided below.

Grade-space spaces:

- Staff appreciated that MSBA is attending to elementary science and technology/engineering in school design.
- Strong appreciation for the inclusion of sinks and work space for science in generalist elementary classrooms.
- Several people mentioned the need for storage at elementary, but did not specified what in particular needed to be stored.
- Input showed an appreciation for the option of a specialized science and technology/engineering room at elementary and the option of a makerspace.
    - Also acknowledgement and appreciation that such rooms require dedicated staff.
- Agreement on the importance of flexibility in STEM spaces to accommodate variety of curriculum activities.
- Several questioned the assumption of 24 students as the basis for class size; in each case they noted that typical class sizes were larger in their school.
- One proposed draft recommendation we made was to define the size of 6^{th} grade science labs as being equivalent in size to elementary specialist rooms (smaller than other middle school science labs). Staff who commented on this typically felt that overall school flexibility was more important (that room may not always be a sixth grade room) and that sixth grade was more like 7^{th} and 8^{th} grade than elementary grades. There was better support for a smaller room when and if the 6^{th} grade science room was included in an elementary school rather than a middle school.
- Feedback indicated that not including an acid neutralization system or holding tank is fine; it would not substantively impact the program.
- People appreciated contextualizing makerspaces in relationship to more typical technology education (tech ed) spaces; that makerspaces are not a new category of space but an evolution of spaces already present in schools.
- Staff expressed an appreciation for understanding the shift in tools and equipment available in makerspaces as compared to traditional shops or tech ed spaces, particularly the inclusion of digital tools (machines that are programmed).

Balancing costs

- People recognized the cost of including of some elements (such as sinks in elementary classrooms), and that funds are limited in districts. They also recognized those places where costs can be reduced (such as not needing an acid neutralization system in middle and high school science labs).
- A key received message was the importance of staff training for both safety in and management of STEM spaces. Many asked where training can be obtained, or where such resources can be found. A number of people expressed concern that there is not or would not be funding to provide appropriate safety equipment or training in their district.

Open questions

- What are some implications of designs where students across a wide range of grades (e.g., K through 8) share the same STEM space (such as a makerspace)?
- Where can safety training be obtained, or what resources are available?

About the authors

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STEM Learning Design supports school redesign and STEM program design that reflects a school's mission and future student needs, with an emphasis on how design plays out in classroom space and use. As past STEM leader at the Massachusetts Department of Elementary and Secondary Education, Jake has significant knowledge, understanding, and experience with education policy, STEM programming, professional development, school support, and strategies for systemic change. He was a lead developer and writer of the Massachusetts Science and Technology/Engineering Standards and standards for Digital Literacy and Computer Science. He was a member of the Next Generation Science Standards writing team, and Massachusetts' representative for the NGSS development process collaborating with 22 other states. Jake was a member of the MSBA high school science lab committee (~2009–2010) to inform the 2011 guidelines. Jake's early career included teaching high school physical and earth sciences, coaching middle school educators, and preservice teacher education. fosterjg@verizon.net

Laura Smith
Contributing Consultant

Laura began her career as an elementary and middle school teacher then went on to coordinate PreK–5 district curriculum, all with a strong focus on science. In these roles she has supported initiatives to build science classrooms in district elementary schools and STEM laboratories in middle school. She trained staff on science laboratory and technology/engineering safety procedures, evaluated classrooms to ensure they met safety standards, educated building administrators on safety requirements, and maintained supplies in the district. Laura continues her work by providing professional development to unpack the Massachusetts STE and NGSS Standards to support quality instruction, curriculum alignment, and assessment development. She is a Board member of the Massachusetts Science Education Leadership Association and a science educator in the STEM Education and Teacher Development Department at UMass Dartmouth.