BUILDING COMPUTATIONAL LITERACY THROUGH STEM EDUCATION: A GUIDE FOR FEDERAL AGENCIES AND STAKEHOLDERS

A Report by the

COMPUTATIONAL LITERACY INTERAGENCY WORKING GROUP

FEDERAL COORDINATION IN STEM EDUCATION SUBCOMMITTEE

COMMITTEE ON STEM EDUCATION

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

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The Committee on STEM Education (CoSTEM) was established pursuant to the requirements of Section 101 of the America COMPETES Reauthorization Act of 2010 (42 U.S.C. §6621). In accordance with the Act, the Committee reviews science, technology, engineering, and mathematics (STEM) education programs, investments, and activities, and the respective assessments of each, in federal agencies to ensure that they are effective; coordinates, with the Office of Management and Budget, STEM education programs, investments, and activities throughout the federal agencies; and develops and implements through the participating agencies a STEM education strategic plan, to be updated every five years.

About the Federal Coordination in STEM Education Subcommittee

The Federal Coordination in STEM Education (FC-STEM) is a subcommittee of the NSTC Committee on STEM Education (CoSTEM). FC-STEM advises and assists CoSTEM and serves as a forum to facilitate the formulation and implementation of the strategic plan. Six Interagency Working Groups (IWGs) support FC-STEM as it implements the Strategic Plan and brings together members who represent the federal government’s foremost experts in STEM education.

About the Interagency Working Group on Computational Literacy

Computational literacy has been identified as one of four pathways with cross-cutting approaches to achieve the vision and goals of the 2018 Federal STEM Education Strategic Plan. This pathway acknowledges how thoroughly digital devices and the internet have transformed society and seeks to adopt strategies that empower learners to take maximum advantage of this change. It recognizes that digital literacy empowers people with the tools to find information, answer questions, and share ideas and that they need to understand how to use these tools responsibly and safely. The Computational Literacy Interagency Working Group (IWGCL) was established to facilitate building computational literacy through STEM education heavily imbued with computational skills and accessed through digital means.

About this Document

The Federal STEM Education Strategic plan recognizes the importance of building computational literacy today. This document is aligned to the IWGCL objectives to: (1) develop a common operational definition; (2) identify existing research on computational literacy; and (3) identify existing research-based model programs, content and curriculum, best practices and other measurable quantities that inform successful examples of building computational literacy in STEM education in both federal and non-federally sponsored research and programs. The intended audience of this report is federal agencies and other STEM education stakeholders, to support the understanding and implementation of computational literacy in STEM education.

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Abbreviations and Acronyms

AI	Artificial intelligence
CoSTEM	Committee on STEM Education
DEIA	Diversity, Equity, Inclusion, and Accessibility
DHS	Department of Homeland Security
DOC	Department of Commerce
DoD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
DOL	Department of Labor
DOT	Department of Transportation
ED	Department of Education
FC-STEM	Federal Coordination in STEM Education Subcommittee
FDA	Food and Drug Administration
HHS	Health and Human Services
IT	information technology
IoT	internet of things
IWG	Interagency Working Group
IWGC	Interagency Working Group on Convergence
NASA	National Aeronautics and Space Administration
NICE	National Initiative for Cybersecurity Education
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
NITRD	Networking and Information Technology Research and Development Program
NOAA	National Oceanic and Atmospheric Administration
NSF	National Science Foundation
NSTC	National Science and Technology Council
OMB	Office of Management and Budget
OSTP	Office of Science and Technology Policy
SI	Smithsonian Institution
STEM	science, technology, engineering, and mathematics
USDA	United States Department of Agriculture
USGS	United States Geological Survey
USPTO	United States Patent and Trademark Office
VA	Department of Veterans Affairs

Executive Summary

President Biden has been clear: American science, technology and innovation—and the people that fuel it—are key to achieving our nation's great aspirations: ensuring robust health and plentiful economic opportunity for every person; tackling the climate crisis and transitioning to clean energy; investing in creating the industries of tomorrow; and advancing global security and stability[1]. Digital devices and the internet have transformed the way we engage in society, work, and everyday activities, and every individual must have the basic digital knowledge and skills to benefit from technology fully, safely, and securely.

A recent study reported over 90 percent of jobs across industries in the United States require at least some digital skills.[2] Computational literacy components are needed to provide on-ramps to good jobs and stable careers. Computational literacy also promotes digital resilience and prepares people to adapt to the changing demands for skills.[3] Today's students are tomorrow's software and application developers; data and business analysts; artificial intelligence, machine learning, and cybersecurity specialists; digital content developers; environmental and renewable energy engineers; automation technicians; quality control inspectors; and quantum information scientists. They are also tomorrow's teachers, nurses, entrepreneurs, customer service representatives, physical therapists and more. The benefits of computational literacy can help all ages, including those who pursue careers in fields beyond science, technology, engineering, and mathematics (STEM).

A computationally literate country is necessary to promote innovation and competitiveness, and to build a workforce that can enhance national security, promote economic prosperity, and improve our quality of life. Computational and communication technologies are rapidly evolving and creating challenges to traditional instructional methods. Educational technology can improve learning. All Americans need equitable access to educational technology, including sufficient high-speed internet access.

This guide identifies and promotes best practices in building computational literacy in STEM education. It includes examples of practices regarding online learning, diversity, equity, inclusion and accessibility, examples of successful integration of computational literacy in STEM education, and examples of computational literacy through the lens of emerging technologies. This report also includes resources for federal agencies and education stakeholders to incorporate components of computational literacy in STEM education at all levels. As STEM-serving disciplines expand, so too does the demand for computational literacy instruction necessary for the workforce of today and beyond.In addition, addressing issues of access is critical for improving computational literacy across the nation. Closing the digital divide is an important step in enabling all learners to fully participate in the digital economy. This guide includes recommendations to address the barriers and improve access across four areas: (1) fundamental digital skills, (2) teacher professional development, (3) ethics, and (4) community outreach. Equipped with computational literacy tools, America's workforce will have the education, training, and credentials to pursue high-demand jobs and work toward economic prosperity for all.

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1 FACT SHEET: President Biden's 2024 Budget Invests in American Science, Technology, and Innovation to Achieve Our Nation's Greatest Aspirations | OSTP | The White House

2 National Skills Coalition, https://nationalskillscoalition.org/wp-content/uploads/2023/02/NSC-DigitalDivide_report_Feb2023.pdf

3 Digital US Coalition. (2020). Building a Digitally Resilient Workforce: Creating On-Ramps to Opportunity, https://digitalus.org/wp-content/uploads/2020/06/DigitalUS-Report-pages-20200602.pdf

Introduction

Computational literacy has become increasingly important for all generations as digital assets and computation are increasingly embedded into the processes and tools we use as a society, at work, and in everyday activities. A computationally literate society is necessary to promote innovation and competitiveness and to build a workforce that can enhance national security, promote economic prosperity, and improve our quality of life.

Recognizing the need for developing a computational literate populace, the federal STEM Education Strategic Plan, *Charting a Course for Success: America's Strategy for STEM Education*,[4] included computational literacy as one of the four cross-cutting pathways to achieve the plan's educational goals. In 2019, the Computational Literacy Interagency Working Group (IWGCL) was established to "build computational literacy through STEM education heavily imbued with computational skills and accessed through digital means."[5] Further, to measure effectiveness of initiatives, as stated on page 31 of the federal STEM Education Strategic Plan, "in the implementation phase of the plan, agencies will work together to develop appropriate metrics, for tracking progress towards the goals and objectives, taking into account the variable nature of federal programs, investments, and activities…an open, collaborative interagency process will be needed to coordinate the further development of common definitions and outcome metrics."

The Process of Developing a Definition

In 2020, IWGCL began conducting a literature review on computational literacy education to explore actions that would facilitate building computational literacy in STEM education. With the continued growth in science and engineering knowledge and the rapid progression of technology, the need for computational literacy education has only been amplified.

The initial literature review revealed varying interpretations of computational literacy as viewed through each federal agency's lens, as well as externally by academia, industry, and across the scientific and education enterprise. As STEM continues to expand to new fields of emphasis to include data science, cybersecurity, artificial intelligence, privacy, quantum, and space science, educational complexity also expands to integrate new understandings in STEM teaching and learning. Each field seeks to expand, diversify, and strengthen the workforce within their individual discipline, and increasingly through the convergence of disciplines. However, there are underlying skills that are common across these areas, specifically, the skills found in computational literacy.

IWGCL determined its effectiveness could be hampered by the lack of a common definition of computational literacy, particularly within the context of the growing STEM landscape. Commonality of skills is difficult to identify when each group has a different name for the same thing and stresses specific areas of importance. Therefore, IWGCL took on this task to determine an agreed upon definition to unify how best to build computational literacy across STEM education.

A definition of computational literacy provides a common lexicon that describes the components of computational literacy, while not prescribing or constraining any particular use of the term or emerging

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4 Committee on STEM Education of the National Science and Technology Council. (2018). *Charting a Course for Success: America's Strategy for STEM Education.* Executive Office of the President of the United States. https://trumpwhitehouse.archives.gov/wp-content/uploads/2018/12/STEM-Education-Strategic-Plan-2018.pdf

5 Op. cit.

definitions as technological and computational advances progress. Using a consistent definition across the federal government will strengthen agencies' ability to communicate consistently and clearly to enable all people to actively participate in the global digital economy.

In developing a working definition, the IWGCL considered input from many sources, including:

- The federal STEM Education Strategic Plan which noted several components important in the development of computational literacy in STEM education. Components mentioned included digital fluency, cybersafety, cyberethics, cybersecurity, data privacy, data security, confidentiality, ethical data use, intellectual property, computational thinking, digital literacy, data science and modeling, artificial intelligence, human dimensions of cyberethics, safety, and security, and effective uses of distance learning models, and digital platforms and accessibility tools.
- Public responses from the *Request for Information on STEM Education*[6] regarding the components and key concepts or topics to be included in efforts to build computational literacy in STEM education. These responses were reviewed and provided additional perspectives around interpretations of computational literacy.[7]
- Current research-based educational practices across grades to build computational literacy in STEM education. Insights surfaced an increasing emphasis on current topics such as data science, data literacy, cybersecurity, artificial intelligence, quantum computing, computational science, computer science, engineering, and other computationally intensive related STEM fields.

IWGCL's definition of *Computational Literacy* for federal agencies is intended to help clarify the characteristics and components in building computational literacy that are easily recognized by potential applicants and partnering institutions. It is intended as foundational language and can be adjusted to fit the needs of a specific federal agency, program, or activity. An agreed upon federal nomenclature demonstrates a strengthened federal commitment to promote the teaching and learning of computational literacy in STEM education; provides clarity and a means for common metrics to enable accurate reporting of federal agency actions; and helps states, tribal communities, regions, local entities, and military communities promote and implement computational literacy in STEM education, training, and research.

Using a consistent definition can improve the communication needed to identify, recruit, and retain a digital workforce that ensures a consistent flow of skilled workers capable of conceptualizing and solving the nation's critical scientific problems. In addition, meeting the demands for competitiveness requires opportunities to teach and learn using the tools and methods of the economy of the future, creating opportunities to build computational literacy through STEM education at all educational levels. A common nomenclature will allow academia and employers to use focused, consistent language in professional development programs, in their use of industry certifications and academic credentials, and in their selection of relevant training opportunities for their workforce. It will also provide an established lexicon that academic institutions can use to develop curricula that better

[6] Notice of Request for Information on STEM Education. https://www.federalregister.gov/documents/2020/09/04/2020-19681/notice-of-request-for-information-on-stem-education

[7] See Appendix 1 for a summary of data analysis of public comments.

prepare students to engage in a global interconnected setting and prepares them to thrive and prosper in the current and future workplace.

Computational Literacy: Definition

Computational Literacy is the ability to use information, information processing agents, digital assets, networking components, and applications and systems that, combined, allow people and organizations to interact in a digital world and solve problems, either individually or with a team; to draw meaning and reasonable conclusions from digital information in both personal and professional contexts; to safely, ethically, and securely use networks (wired and wireless) and data; and to understand how computing, data, and connectivity affects society. Essential components also identify the social and cultural contexts that include how society engages in the use of technology and how to ensure such use is for the benefit of society. Computational literacy helps an individual -

- *(A) ethically, securely, safely, and efficiently use information processing agents, digital tools, and digital platforms to teach, learn, and solve problems, including problems with sensitive information.*
- *(B) problem solve (e.g., decomposing problems into manageable pieces; heuristic reasoning; algorithmic thinking; computational thinking).*
- *(C) think recursively.*
- *(D) navigate multiple levels of abstraction.*
- *(E) recognize patterns.*
- *(F) collect, analyze, manage, visualize, and communicate data.*
- *(G) translate domain knowledge into mathematical and visual model.*
- *(H) understand the social, technical, and cultural dynamics of computational technology, including equity, inclusion, and accessibility.*
- *(I) critically evaluate information, data, and technologies.*

This report's working definition was prepared by the Computational Literacy Interagency Working Group under the Federal Coordination in STEM Education Subcommittee (FC-STEM) of the Committee on STEM Education (CoSTEM). It was reviewed by member agencies of FC-STEM and revised following agency feedback.

Following extensive research and input from multiple stakeholders, the Computational Literacy IWG created the above definition.

Defining Computational Literacy

Literacies, including computational literacy, are essentially diverse. Literacies, ultimately over time change the way we think and understand. There is always social dialogue in their development, and, quite predictably, a phase of self-conscious promotion and active spread.[8] Different disciplines will determine how the literacy best serves them and interpretations may vary as viewed through each federal agency's lens. Agencies are encouraged to use CoSTEM's definition of computational literacy in their programs and activities that support computational literacy in STEM education at all levels and in both schools and out-of-school STEM activities. Computational literacy is necessary to engage in the interconnected economy and to be competitive and excel in today's workforce. A computationally literate populace is needed to drive innovation and create the conditions for building a workforce that can enhance national security, promote economic prosperity, and maintain global competitiveness.

Current State of Computational Literacy

Digital technologies are pervasive both at home and at work. Many people engage routinely in day-to-day online activities from banking transactions to ordering products. The definition of computational literacy recognizes the critical component of digital literacy skills. To understand how equipped individuals are for successful participation in 21st-century society and the global economy, the Organization for Economic Cooperation and Development (OECD) has developed the Program for the International Assessment of Adult Competencies (PIAAC). PIAAC is a cyclical, large-scale study for ages 16 and over around cognitive skills and life experiences and is conducted in the United States by the National Center for Education Statistics (NCES). PIAAC measures the key cognitive and workplace skills of reading literacy, numeracy (the ability to understand and work with numbers), and the ability to solve problems using technologies. The OECD refers to this third skill as "problem solving in a technology rich environment," also referred to as "digital problem solving," which closely aligns with our definition of computational literacy.

PIAAC assesses digital problem solving by simulating tasks commonly performed in computer-based settings. There are four proficiency levels in digital problem solving from below Level 1 to Level 3. At problem solving proficiency Level 1, adults can be considered nearing proficiency (Level 2) but still struggling with digital problem solving. In the latest round of PIACC, 24 percent of Americans scored below Level 1 based on the PIAAC International average score, 38 percent scored at Level 1, 32 percent at Level 2, and 6 percent of the population surveyed scored the highest, Level 3 and above.[9]

In addition, the United States participated in the 2018 International Computer and Information Literacy Study (ICILS) along with 13 other countries. ICILS is sponsored by the International Association for the Evaluation of Educational Achievement (IEA) and assesses 8th-grade students in two domains: computer and information literacy (CIL) and computational thinking.[10] The ICILS compares U.S. students' skills using technology to that of students in other countries' education systems and

[8] Recognizing that literacies are the convergence of social groups' use of common representational forms, a computational literacy definition is complex and different groups with different intellectual foci, will have a diverse and variegated meanings emerge. Directly representing complex processes is a major new contribution of computational literacy.

[9] "Highlights of PIAAC 2017 U.S. Results, https://nces.ed.gov/surveys/piaac/national_results.asp; "A Description of U.S. Adults who are not Digitally Literate," https://nces.ed.gov/pubs2018/2018161.pdf

[10] U.S. Results from the 2018 International Computer and Information Literacy Study (ICILS) Web Report (NCES 2019-164). U.S. Department of Education. Institute of Education Sciences, National Center for Education Statistics. Available at https://nces.ed.gov/surveys/icils/icils2018/theme1.asp.

provides information on factors such as teachers' experiences and school resources that may influence students' CIL and computational thinking skills.

The NCES reports that, "the U.S. 8th-grade students' average score in CIL was higher than the ICILS 2018 average, while the U.S. average score in computational thinking was not significantly different from the ICILS 2018 average. In the United States, female 8th-grade students outperformed their male peers in CIL, but male 8th-grade students outperformed female students in computational thinking. Also, U.S. 8th-grade students with two or more computers at home performed better in both CIL and computational thinking than their U.S. peers with fewer computers. Among U.S. 8th-grade students, 72 percent reported using the internet to do research every school day or at least once a week, and 65 percent reported teaching themselves how to find information on the internet. About half of U.S. 8th-grade teachers reported using information and communications technologies (ICT) in teaching. Eighty-six percent of U.S. 8th-grade teachers strongly agreed or agreed that ICT was considered a priority for use in teaching at their schools. Compared with the ICILS 2018 averages, higher percentages of U.S. 8th-grade teachers reported participating in eight out of nine professional learning activities related to ICT."[11]

Education increasingly relies on computers and internet access. National data reveals that 70 percent of teachers assign homework that requires access to broadband and 30 percent of school districts in the United States include technology in their curricula. Students and educators engage in numerous activities and tasks online, from conducting research, watching and reading education materials, and engaging in educational simulations and data visualization exercises. Data show that students with fast internet access at home utilize additional opportunities such as working on projects with peers, seeking homework advice, and emailing teachers and peers more regularly and more often than students without that access. Students with no or limited internet access or who rely on cellphones only, use their online networks significantly less than students with fast internet access.

Bauer found that students with only cellphone access have lower digital literacy and social media skills and lower rates of homework completion, which in turn are associated with lower grade point averages and standardized test scores.[12] Fairlie, Beltran, and Das found that high school students with broadband internet access at home have 6–8 percentage points higher graduation rates than students without broadband access,[13] and KewalRamani et al., found that students with home internet access score higher in reading, math, and science.[14] Digital inequality affects more than just homework completion and test scores. Research by Hampton et al., revealed that students without broadband internet access also indicated enjoying school less, experienced lower self-esteem, had lower digital skills, lower interest in STEM-related careers, and felt disadvantaged in pursuing post-secondary education opportunities.[15] Recognizing the beneficial uses of technology and digital access, some

[11] ICILS 2018 U.S. Results. (2019). U.S. Department of Education, Institute of Education Sciences, National Center for Education Statistics. https://nces.ed.gov/surveys/icils/icils2018/theme1.asp

[12] Bauer, J. (2020). What COVID-19 underscores about how broadband connectivity affects educational attainment. The Pew Charitable Trusts. https://www.pewtrusts.org/en/research-and-analysis/articles/2020/12/08/what-covid-19-underscores-about-how-broadband-connectivity-affects-educational-attainment

[13] Fairlie, R. W., & Robinson, J. (2013). Experimental Evidence on the Effects of Home Computers on Academic Achievement among Schoolchildren. *American Economic Journal: Applied Economics*, 5(3), 211-240. https://www.aeaweb.org/articles?id=10.1257/app.5.3.211

[14] KewalRamani, A., Zhang, J., Wang, X., Rathbun, A., Corcoran, L., Diliberti, M., & Zhang, J. (2018). Student Access to Digital Learning Resources Outside of the Classroom (NCES 2017-098). U.S. Department of Education. Washington, DC: National Center for Education Statistics. https://nces.ed.gov/pubsearch/pubsinfo.asp?pubid=2017098

[15] Hampton, K., Fernandez, L., Robertson, C., & Bauer, J. M. (2020). Broadband and student performance gaps. Quello Center, Michigan State University. https://quello.msu.edu/wp-content/uploads/2020/03/Broadband_Gap_Quello_Report_MSU.pdf

school districts have started to loan out notebooks and hotspots to students to use at home. However, installing Wi-Fi hotspots in school buses or using school buses to provide decentralized Wi-Fi access, which increased during the pandemic, proved to be less effective, because these uses are time-limited and not fully comparable to home use.[16]

Home internet helps students develop and expand their digital skills outside of the academic setting. The coronavirus pandemic exposed the individual and social costs of limited or no connectivity to American households. Depriving numerous individuals and families from academic engagement, health care resources, and government services brought about temporary service provider changes. The Federal Communications Commission relaxed rules around the E-Rate program, a federal effort that provides broadband to schools and libraries.[17] This E-Rate change allowed schools and libraries to extend Wi-Fi access and funding from the Coronavirus Aid, Relief, and Economic Security (CARES) Act enabled schools to purchase devices and hotspots. These and other philanthropic and community service activities were tremendously helpful, and they accelerated the development of innovative approaches to overcoming digital inequalities.

Broadband has become influential on society and is part of the communications industry—one of the 16 recognized critical infrastructure sectors. Similarly, broadband access is critical to developing a computationally literate society . Despite its importance, broadband is still far from ubiquitous. Millions of households do not have access to high-speed wireline or wireless services, and many more lack the digital skills or income to use online services. These gaps persist across every state, regardless of density levels, from small towns to urban neighborhoods, and among demographic groups of all races, educational attainments, and income.

Barriers to Building Computational Literacy

In fall of 2020, on behalf of the National Science and Technology Council's (NSTC's) Committee on STEM Education (CoSTEM) and in coordination with the White House Office of Science and Technology Policy (OSTP), the National Science Foundation (NSF) released a public request for information (RFI) to support the implementation of the Federal STEM Education Strategic Plan, and to better understand the impacts of the COVID-19 pandemic on learners and educational institutions.[18] Responses to RFI questions related to computational literacy were analyzed and coded into emerging themes. There were 115 respondents with varied backgrounds including teachers, state governments employees, students, university and community college faculty, education-based non-profit and for-profit stakeholders, and federally funded program recipients. Additional data were gathered through conference convenings and workshops, in addition to the literature review to triangulate data to increase the credibility and validity of findings. More details on the analysis of the RFI responses can be found in Appendix 1.

The following themes emerged as key challenges of integrating computational literacy within STEM curriculum.

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16 Bauer, J. (2020). What COVID-19 Underscores About How Broadband Connectivity Affects Educational Attainment.

17 The schools and libraries universal service support program, commonly known as the E-rate program, helps schools and libraries to obtain affordable broadband. https://www.fcc.gov/general/e-rate-schools-libraries-usf-program

18 STEM Education Request for Information. https://www.govinfo.gov/content/pkg/FR-2020-09-04/pdf/2020-19681.pdf .

MISCONCEPTIONS

- Interpretations included a wide range of skill sets and topics.
- Computer science exclusivity: Siloed thinking that computational literacy means CS only, or must require advanced levels of technology.
- Lack of appreciation for the wide range of computational skills including software development, data visualization, statistics, machine learning, ethics, safety and cybersecurity, and working with large computational infrastructure

INSTRUCTOR EXPERIENCE/KNOWLEDGE

- Lack of expertise in instructors: Most teachers have not been formally training in CL, or in curriculum integration
- Ineffective implementation: Superficial integration can leave students without the depth of experience necessary to develop computational literacy
- Limited application of technology: Tech used mainly for simulations; coding in a vacuum; no real-world or hands-on elements

STATE EDUCATION POLICIES

- Integrating CL is considered a secondary priority to traditional subjects
- Lack of funding and accountability for districts to do implementation work
- Insufficient depth of implementation: CL in afterschool programs are restricted to a sample of students; not embedded in the curriculum

Image 1: Summary of the main themes from RFI on the challenges of integrating computational literacy within a STEM curriculum.

Additional barriers related to diversity, equity, inclusion, and accessibility are discussed in a succeeding section. The report on "Best Practices for Diversity and Inclusion in STEM Education and Research,"[19] drafted by the Interagency Working Group on Inclusion in STEM (IWGIS), helped guide the work of the IWGCL to explore potential ways to address these challenges.

Computational Literacy Research and Best Practices

The IWGCL curated research on computational literacy in both federal and non-federally sponsored efforts and identified existing research-based model program content and curriculum; best practices (evidence-based, promising, and emerging practices);[20] and other measurable quantities that would inform successful examples of building computational literacy in STEM education at all levels. Findings also provided guidance to overcome some of the reported barriers noted in the prior section in building computational literacy in STEM education.

The format of each section may vary depending on the available research and information on the topic or the types of computational literacy related programs that are currently being implemented by organizations.

Computational Literacy with Online Learning

Online learning has expanded and extended the period throughout a day that can be dedicated to learning. Education no longer stops once the final school bell rings. With the rise of digital assets and technical innovations during the 21st century, people gained access to vast amounts information at a

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19 Interagency Working Group on Inclusion in STEM. (2021). Best Practices for Diversity and Inclusion in STEM Education and Research: A Guide by and for Federal Agencies. https://www.whitehouse.gov/wp-content/uploads/2021/09/091621-Best-Practices-for-Diversity-Inclusion-in-STEM.pdf

20 This report uses the definitions of best practices adopted by CoSTEM's Interagency Working Groups, to include evidence-based, promising, and emerging practices. Interagency Working Group on Inclusion in STEM. (2021). Best Practices for Diversity and Inclusion in STEM Education and Research: A Guide by and for Federal Agencies. https://www.whitehouse.gov/wp-content/uploads/2021/09/091621-Best-Practices-for-Diversity-Inclusion-in-STEM.pdf

moment's notice. While acquiring this information (provided there is adequate internet access) is relatively easy, some users are more adept or prepared to take advantage of the plethora of online learning opportunities than others.[21] A review of the literature on best practices of online learning was completed to help assist government agencies as they develop computational literacy content for learners of all ages. This section aims to identify some major themes for consideration in building computational literacy through online learning.

Considered to be a subset of distance learning, online learning is also referred to as web-based training, e-learning, distributed learning, internet-based learning, web-based instruction, "just-in-time" learning, cyber learning, virtual learning, or net-based learning.[22] Today, teaching and learning online is done through a wide range of technical applications helping to address multiple learning processes. The drill-based practice and computer-assisted learning of the 1970s and 80s evolved into more interactive multimedia and computer-based learning designs. Internet access led to web-based training, virtual classrooms and digital collaborations, eLearning platforms (e.g., massive online open courses, learning management systems) and most recently, learning with social networking components and with portable technologies where the focus is on the mobility of the learner. In addition, more innovative applications such as simulations, educational games, interactive assets, and cyber ranges allow individuals to gain a greater understanding of the concepts and apply the skills in creating solutions for real-world problems. For this document, online learning will be defined as:

> *[t]he use of digital assets to access learning materials; to interact with the content, instructor, and other learners; and to obtain support during the learning process, in order to acquire knowledge, to construct personal meaning, and to grow from the learning experience.*[23]

Studies show that the attitude of a learner has an impact on learning outcomes and the success or failure of online learning.[24] The foundation of a learner's comfort level with digital learning, often referred to as Information and Communications Technology (ICT), can be directly correlated to a learner's attitude towards online learning.[25] Furthermore, building computational literacy and comfort in all learners (and educators) ensures that should learners have to leave school for extended periods of time like during a pandemic they are well positioned to continue their learning objectives with little to no interruption in school curriculum.[26] The best way to build positive attitudes among learners is through continual exposure to digital content.[27] Placing equal focus on digital communication—as is traditionally given to oral and written communication teachings in the classroom provides greater comfort and helps improve attitudes towards online learning. This foundation-setting increases the

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[21] Lung-Yu Li, & Lee, Long-Yuan. (2016). Computer Literacy and Online Learning Attitude toward GSOE Students in Distance Education Programs. *Higher Education Studies*, 6(3). https://files.eric.ed.gov/fulltext/EJ1111001.pdf

[22] Urdan, T. A., & Weggen, C. C. (2000). Corporate e-learning: Exploring a new frontier. WR Hambrecht Co. http://papers.cumincad.org/data/works/att/2c7d.content.pdf

[23] Ally, M. (2008). Foundations of educational theory for online learning. *The Theory and Practice of Online Learning* (2nd ed., 15-44). https://eddl.tru.ca/wp-content/uploads/2018/12/01_Anderson_2008-Theory_and_Practice_of_Online_Learning.pdf

[24] Li, Lung-Yu, & Long-Yuan Lee. (2016). Computer Literacy and Online Learning Attitude toward GSOE Students in Distance Education Programs.

[25] Peytcheva-Forsyth R., Yovkova B., & Aleksieva, L. (2018). Factors affecting students' attitudes towards online learning - The case of Sofia University, AIP Conference Proceedings 2048, 20025. https://doi.org/10.1063/1.5082043. Kintu, M.J., Zhu, C. & Kagambe, E. Blended learning effectiveness: the relationship between student characteristics, design features and outcomes. *Int J Educ Technol High Educ* 14, 7 (2017). https://doi.org/10.1186/s41239-017-0043-4

[26] Montoya S., & Barbosa, A. (2020). The importance of monitoring and improving ICT use in education post-confinement. UNESCO Institute for Statistics. https://uis.unesco.org/en/blog/importance-monitoring-and-improving-ict-use-education-post-confinement.

[27] Zhu, Y., Au W., & Yates G. (2013). University students' attitudes toward online learning in a blended course. AARE Annual Conference, Adelaide. https://files.eric.ed.gov/fulltext/ED603297.pdf

potential for future realization in positive learning attitudes towards online learning and begins at the earliest possible ages with children learning to use digital content at home through play with best practices extending ICT play into school classrooms.[28]

When developing the structure of online learning, it has been shown that the quality of the instructional design of the content significantly impacts the learning outcomes.[29] This plays out in designing a healthy balance of both asynchronous and synchronous learning.[30] This blended-learning approach offers flexibility allowing learners to control the pace of their learning while also affording a deeper understanding of learning objectives.[31]

Another best practice for online learning that Rappolt-Schlichtmann discusses, is creating a supportive community with selective time for check-ins with learners.[32] Building a network in which learners can interact with instructors and classmates can reduce social isolation and build a sense of connectedness and belonging. This learner support helps provide context, which is important. It also makes available opportunities for learners to contextualize and process information received allowing for a deeper understanding by applying what is learned in real life.[33] Another advantage to a strong support system in online learning is that it creates learner satisfaction. With learner satisfaction comes increased motivation and, more specifically, intrinsic motivation.[34] There are a variety of different ways to build in support such as communication tools that provide a means for learners to connect and have meaningful discussions that build over time, pre-scheduled weekly meetups between learners to facilitate dialogue of course content, or instructor-learner meetings to provide “face to face” connectedness and encourage question asking. These are just a few of things that can be judiciously incorporated into online learning to create a support community where learners may flourish.

With the onset of the COVID-19 pandemic forcing schools to quickly switch to online learning, computational literacy deficiencies in our educational systems for both educators and students were exposed. Through dedicated and calculated crafting of computational literacy online content delivery for learners at all levels, positive attitudes towards online learning can be shaped, especially in our youngest learners who are already growing up in an interconnected society. By following a vigilant approach to shaping blended online learning, the habits, motivation, and satisfaction of learners can all be guided through building supportive communities using online learning environments.

Diversity, Equity, Inclusion, Accessibility, and Computational Literacy

One goal of the Federal STEM Education Strategic Plan is to increase diversity, equity, and inclusion in STEM. In seeking to improve the pathways to build computational literacy, it is important to consider and address issues regarding diversity, equity, inclusion, and accessibility (DEIA). IWGIS released a

[28] Nikolopoulou K. (2015). ICT – Computer Play and Children‘s Development of Skills in Science. *International Journal of New Technology and Research*, 1(5), 18-22. https://www.ijntr.org/download_data/IJNTR01050013.pdf

[29] Hudson, E. (2020). What Research Does—and Does Not—Tell Us About On-line Learning. Global Online Academy. https://globalonlineacademy.org/insights/articles/what-research-does-and-does-not-tell-us-about-online-learning

[30] Rappolt-Schlichtmann, G. (2020). Distance learning: 6 UDL best practices for online learning. https://www.understood.org/en/articles/video-distance-learning-udl-best-practices

[31] Garrison R.D., & Kanuka H., Blended Learning: Uncovering its transformative potential in higher education. *The Internet and Higher Education,* 7(1), 95–105. https://doi.org/10.1016/j.iheduc.2004.02.001

[32] Rappolt-Schlichtmann, G. Distance Learning: 6 UDL Best Practices for Online Learning.

[33] Ally, M. Foundations of Educational Theory for Online Learning.

[34] Kintu, M. J. et al. Blended Learning Effectiveness: The Relationship Between Student Characteristics, Design Features and Outcomes.

report on best practices for diversity and inclusion in STEM for federal agencies.[35] While all the noted recommendations in the report can be helpful to federal agencies, several of the recommendations, with a narrowing of focus, apply to computational literacy, including:

- Identify barriers to access and participation in computational literacy integrated in STEM educational programs and partner with other agencies, institutions, and professional organizations to reduce or eliminate the barriers.
- Focus on one or more institutional barriers to building computational literacy in STEM education such as policies, workplace climate, differential compensation packages, data, and peer-to-peer interactions.
- Require program participants and grant recipients to share how they will reduce or eliminate barriers to diversity in building computational literacy in STEM education.
- Focus on one or more individualized barriers to participation in building computational literacy in STEM education and develop programs that address areas such as mentoring, support systems, discrimination, perception of STEM programs, stereotypes and stereotype threat, bias, and STEM identity.
- Focus on one or more barriers impacting the building of computational literacy in STEM education participation for individuals with disabilities.
- Develop policies and practices to ensure DEIA representation in leadership and decision-making bodies to better promote building computational literacy in STEM education.

While there are overarching issues that impact DEIA and computational literacy as a whole; in some cases, finding equitable solutions can be facilitated by looking at some of the issues that specifically impact particular STEM areas, such as cybersecurity.[36]

35 Interagency Working Group on Inclusion in STEM. Best Practices for Diversity and Inclusion in STEM Education and Research: A Guide by and for Federal Agencies. https://www.whitehouse.gov/wp-content/uploads/2021/09/091621-Best-Practices-for-Diversity-Inclusion-in-STEM.pdf

36 Aspen Institute. Diversity, Equity, and Inclusion in Cybersecurity. (2021). https://www.aspeninstitute.org/publications/dei-in-cybersecurity/

Example: A Workshop on Improving DEIA in Cybersecurity

The Aspen Digital Institute conducted two workshops with cybersecurity professionals from academia, government agencies, nonprofits and industry and generated a report to help improve the ecosystem with a goal of increasing DEIA in the cybersecurity workforce. As a field, cybersecurity "remains remarkably homogenous, both among technical practitioners and policy thinkers, and there are few model programs or initiatives that have demonstrated real progress in building diverse and inclusive teams." Further the report estimated that only 4 percent of cybersecurity workers identify as Hispanic, 9 percent as Black, 8 percent as Asian, 1 percent as American Indian, Alaska Native or Native Hawaiian, and 24 percent as women. The recommendations covered several key areas including education, recruitment and hiring, retention, mentorship, and shifting the narrative with the recognition that institutional investment will be required for many of the recommendations to be successfully implemented. A few of the recommendations are highlighted below:

- Organize a coalition to assess the value of certifications in developing quality candidates for cybersecurity jobs
- Establish a group of pro bono experts to help cybersecurity employers rewrite their job descriptions without jargon and focus on the skills required
- Reconsider whether the current criminal background check process is appropriate, fair, and equitable
- Develop a coalition to identify best practices for mentoring diverse cybersecurity practitioners and create shared resources

Addressing issues of access is critical for improving computational literacy across the nation. The digital divide, which is the gap between those who have access to technology, the internet, and digital skills training and those who do not continues to be an important concern. A disproportionate number of those who lack access to a reliable internet connection, devices, and related resources are Black, Hispanic, American Indian, Alaska Native or Native Hawaiian, live in rural areas, or are people whose incomes are below the federal poverty threshold.[37] Closing the digital divide is an important step in enabling all learners with the ability to fully participate in the digital economy of today and tomorrow and in achieving digital equity.

Integration of Computational Literacy in STEM Education

The rapid evolution and application of technologies in a global economy mandates that current and future generations of learners will need to be computationally literate. Using basic digital tools and having foundational digital literacy skills are no longer enough. Workforce occupations across multiple sectors are increasingly requiring more advanced digital skillsets and thought processing that are unique to computational literacy. The K–12 classrooms present an ideal opportunity to start building this literacy, but an individual will continue to gain skills throughout their education and workforce journey. STEM educators are now enormously challenged with becoming proficient in computational literacy themselves and need to effectively implement an ever-growing number of new suites of tools, applications, and course curricula that will engender computation literacy in STEM learning.

[37] https://crpe.org/the-digital-divide-among-students-during-covid-19-who-has-access-who-doesnt/; https://www.pewresearch.org/topic/internet-technology/technology-policy-issues/digital-divide/; https://hbr.org/2021/07/how-to-close-the-digital-divide-in-the-u-s

Successful convergence of computational literacy in STEM education therefore relies heavily on training STEM instructors in computational literacy and providing support from a diverse set of stakeholders. Some important factors include curriculum designers generating computational literacy course materials for STEM disciplines, resources to support classroom technology, educator professional development opportunities, and increasing instructor self-efficacy in computational literacy.

The concept of integrating technology in the classroom is not novel, as research began in the early 1990s setting guidelines for teachers to incorporate computer-assisted instruction at all grade levels.[38] One approach for integrating technology in the classroom that has been gaining momentum in recent years is programming, and this has been heavily implemented in the past decade in the K–12 grades leading to a movement in incorporating coding in some secondary school curricula.[39] However, embedding computational literacy in STEM courses that are not programming centric or computer science courses in general is advantageous, and may be considered an equity strategy to surmount time and accessibility constraints for those who may not be positioned for specific computer science opportunities.[40]

To augment existing STEM pedagogy and curriculum with more advanced computational literacy, some emerging curricular themes have arisen including modeling and simulation, data science, computational problem solving, and systems thinking.[41] These approaches place an emphasis on real-world applicability and can help teachers and students appreciate the value of computational literacy. For example, computer modeling and simulation can prepare students for authentic inquiry in the scientific disciplines, allows manipulation of multiple variables involved in scientific phenomena thereby inherently teaching the scientific process, and is a strategy that facilitates learning through the lens of systems thinking in which the dynamic interactions between multiple parts can be studied. Some examples of computational concept modeling include investigating population dynamics in ecology using *SimBio*[42] software that allows students to vary parameters to understand and predict impacts on animal and plant populations,[43] modeling cell respiration in biology,[44] physical sciences (motion, gas laws, energy), and earth sciences.[45] A commonality shared between all science disciplines is the collection and analysis of data. Using data to introduce computational literacy in all STEM fields has shown to be an effective approach. At the elementary level, students can be introduced to the concepts of data and pattern recognition, later grades can use community science projects to conduct

38 Niess, M. L. (1990). Preparing computer-using educators for the 90s. *Journal of Computing in Teacher Education*, *7*(2), 11-14.

39 Grover, S., & Pea, R. (2013). Computational thinking in K–12: A review of the state of the field. *Educational Researcher*, 42(1), 38-43. https://doi.org/10.3102/0013189X12463051; Lye, S. Y., & Koh, J. H. L. (2014). Review on teaching and learning of computational thinking through programming: What is next for K-12? *Computers in Human Behavior*, 41, 51-61. https://doi.org/10.1016/j.chb.2014.09.012

40 DiSessa, A. A. (2018). Computational literacy and “the big picture” concerning computers in mathematics education. *Mathematical Thinking and Learning*, 20(1), 3-31. https://doi.org/10.1080/10986065.2018.1403544

41 Weintrop, D., Beheshti, E., Horn, M., Orton, K., Jona, K., Trouille, L., & Wilensky, U. (2016). Defining Computational Thinking for Mathematics and Science Classrooms. *Journal of Science Education and Technology*, *25*(1), 127-147. https://ccl.northwestern.edu/2015/Weintrop%20et%20al.%20-%202015%20-%20Defining%20Computational%20Thinking%20for%20Mathematics%20an.pdf

42 https://simbio.com

43 Erkens, R. (2018). Sharing good practices for teaching biogeography. *Frontiers of Biogeography*, 10(1-2). https://doi.org/10.21425/F5FBG37652

44 Bergan-Roller, H. E., Galt, N. J., Chizinski, C. J., Helikar, T., & Dauer, J. T. (2018). Simulated Computational Model Lesson Improves Foundational Systems Thinking Skills and Conceptual Knowledge in Biology Students. *BioScience*, 68(8), 612-621. https://doi.org/10.1093/biosci/biy054

45 Wilensky, U., Brady, C. E., & Horn, M. S. (2014). Fostering computational literacy in science classrooms. *Communications of the ACM*, *57*(8), 24-28. https://dl.acm.org/doi/10.1145/2633031

a data inquiry. *Youcubed* is an emerging resource commonly used by educators to teach data science at all levels of K–12.[46] Furthermore, the plethora of software tools for data visualizations presents an additional and much needed opportunity for computational literacy education that are applicable throughout an individual's education and career pathway.[47] A direct application of computational literacy is using the mathematical and logical skillsets to solve problems**.** Computational problem solving can be applied to solve problems in a variety of STEM subjects and has been shown to improve logical thinking, problem solving, pattern recognition, and navigating multiple levels of abstraction. These implementation practices, if skillfully integrated can be beneficial for reinforcing computational literacy education in all STEM disciplines.

In teacher education research, several key strategies emerged as being critical to computational literacy training, including offering mini workshops, interdisciplinary integration of technology in coursework, modeling the use of technology, using multimedia, collaboration among teachers, mentors for teachers and faculty, practicing technology in the field, and improving access to software, hardware, and IT support. In general, educator programs that incorporate four or more of these teacher professional development strategies can have more persistent effects on teachers' attitudes towards computational literacy classroom integration.[48] However, it is also noted that more rigorous and comprehensive research is needed to fully understand and evaluate the effect of computational literacy professional development strategies in teacher education.[49]

Although some training efforts for designing STEM curriculum with computational literacy are underway for new teachers, several educators are now required to retool to keep abreast of pedagogical advances. As such, educators will require a great deal of professional development and resources to overcome hesitations and increase teacher self-efficacy (TSE). It is well-established that TSE is positively associated with instructor behavior and classroom practices; teachers' personal accomplishment and job satisfaction; and consequently to students' academic adjustment.[50] This is because high TSE has been shown to positively affect teachers' attitudes toward computer use in general.[51] Further, teacher motivation and collaboration in web-based professional development have been strongly linked to computational literacy teaching across several countries,[52] attesting to the global efforts toward incorporating computational literacy in education. Finally, Sang et al., conducted a study on factors affecting the propensity to integrate computational literacy and found that a variety

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46 https://www.youcubed.org/

47 Börner, K., Bueckle, A., & Ginda, M. (2019). Data visualization literacy: Definitions, conceptual frameworks, exercises, and assessments. *Proceedings of the National Academy of Sciences*, 116(6), 1857-1864. https://doi.org/10.1073/pnas.1807180116

48 Kay, R. H. (2006). Evaluating Strategies Used To Incorporate Technology Into Preservice Education: A Review of the Literature. *Journal of Research on Technology in Education*, *38*(4), 383-408. https://files.eric.ed.gov/fulltext/EJ768720.pdf

49 Hsu, T. C., Chang, S. C., & Hung, Y. T. (2018). How to learn and how to teach computational thinking: Suggestions based on a review of the literature. *Computers & Education*, 126, 296-310. https://doi.org/10.1016/j.compedu.2018.07.004; Konstantinidou, E., & Scherer, R. (2022). Teaching with technology: A large-scale, international, and multilevel study of the roles of teacher and school characteristics. *Computers & Education*, 179. https://doi.org/10.1016/j.compedu.2021.104424

50 Zee, M., & Koomen, H. M. (2016). Teacher Self-Efficacy and Its Effects on Classroom Processes, Student Academic Adjustment, and Teacher Well-Being: A Synthesis of 40 Years of Research. *Review of Educational research*, *86*(4), 981-1015. https://journals.sagepub.com/doi/10.3102/0034654315626801

51 Rohaan, E. J., Taconis, R., & Jochems, W. M. (2012). Analysing teacher knowledge for technology education in primary schools. *International Journal of Technology and Design Education*, *22*(3), 271-280. https://doi.org/10.1007/s10798-010-9147-z; Wong, K. T., Teo, T., & Russo, S. (2012). Influence of gender and computer teaching efficacy on computer acceptance among Malaysian student teachers: An extended technology acceptance model. *Australasian Journal of Educational Technology*, *28*(7). https://ajet.org.au/index.php/AJET/article/view/796

52 Konstantinidou, E. et al. Teaching with technology: A large-scale, international, and multilevel study of the roles of teacher and school characteristics.

of teacher-related variables (i.e., TSE, computer self-efficacy, and computer attitudes) influenced the applications of computational literacy in course design.[53]

Current and Emerging Technologies: Convergence of Computational Literacy Components

Throughout history, economic and political forces influence reforms, and the pendulum swings between focus areas. The Association for Supervision and Curriculum Development (ASCD) maintains that historically, in the United States, the purpose of education has evolved according to the needs of society.[54] The central focus has always been to help individuals develop the skills, the knowledge, and the dispositions that will allow them to be responsible and contributing members of their democratically informed community while also contributing to its economic growth and prosperity.

Over the years, several national educational reform movements have taken place. The back-to-fundamentals approach after World War II lasted until the 1950s when Sputnik caused the nation to focus on science, math, engineering, and technical education efforts. Between the 1970s and 1980s, the United States underwent an educational movement toward equality-based and individualized learning. The technology explosion in the 1990s to early 2000s demanded that educators shift their focus back to instruction around the disciplines of science, mathematics, engineering, and technology. In 2001, American biologist Judith Ramaley, then assistant director of education and human resources at the National Science Foundation (NSF), rearranged the words to form the STEM acronym, with the intent to create a new approach to instruction.

The acronym was meant to unite the four fields and highlight how these related disciplines could be taught and content learned in an interdisciplinary way. STEM, as Ramaley states “has science and math serving as bookends for technology and engineering. Science and math are critical to a basic understanding of the universe, while engineering and technology are means for people to interact with the universe.” STEM is more than a class, discipline, course, or knowledge a student can learn from one textbook or degree a student pursues. STEM encompasses a way of learning and provides a way for students to investigate the world around them. Specifically, as viewed through an educational lens:

> ***S*** *stands for Science*, focusing on how students learn about the natural world,
> ***T*** *stands for Technology*, referring to tools and machines, to include computers and digital assets, that are used to solve real-world problems,
> ***E*** *is for Engineering*, studying how things are designed, and
> ***M*** *is for Mathematics*, or the study of numbers, quantities, and space.

Ramaley’s STEM acronym was a way of weaving elements of human action across disciplines into all aspects of education. This multidisciplinary approach was seen as being vital for all students to be successful participants in society. This approach would prepare students to solve interdisciplinary problems that they would encounter in the global society regardless of their major or chosen career path. STEM education would prepare students of all ages to become critical and creative thinkers, innovators, problem-solvers, collaborators, and strong communicators. Interconnecting the STEM

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[53] Sang, G., Valcke, M., Van Braak, J., & Tondeur, J. (2010). Student teachers’ thinking processes and ICT integration: Predictors of prospective teaching behaviors with educational technology. *Computers & Education*, 54(1), 103-112. https://www.sciencedirect.com/science/article/abs/pii/S0360131509001870

[54] ASCD. (2012). What is the Purpose of Education? Infographic. https://www.ascd.org/ASCD/pdf/journals/ed_update/eu201207_infographic.pdf

disciplines through a holistic lens focused on building critical thinking and analysis skills by addressing how students viewed and experienced the world around them. Put simply, the STEM educational approach, often referred to as STEM literacy, would prepare individuals to tackle the challenges of a fiercely competitive and constantly changing global economy.

Although the attention on STEM education has brought with it benefits, the educational system is in danger of losing the innovative collaborative approach. Over time, the interdisciplinary nature of STEM has faded. Instead, Science, Technology, Engineering, and Mathematics are presented as individual, often siloed disciplines. Computer science, cybersecurity, data science, and quantum are just a few of the disciplines that have joined these four key fields and are critical to maintaining our world economic status. Yet, there are common components found within all these disciplines: computational literacy. Computational literacy serves as a lynchpin for the convergence of these disciplines.

The following section highlights how the elements of computational literacy apply to current and future areas and the workforce.

Computational Literacy in Artificial Intelligence

Computational literacy education has long included artificial intelligence (AI) as a subtopic, but the term "AI literacy" began to emerge on its own beginning 2016.[55] Researchers each had their own interpretation of the term, but recently there have been attempts to formally conceptualize AI literacy. An exploratory review of works explicitly using the term "AI literacy" revealed four main competencies put forth by prior researchers: (1) to know and understand the basic functions of AI and AI-driven applications, (2) to use and apply AI concepts to different scenarios, (3) to evaluate and create AI, and (4) to be conversant in AI ethics.[56] A thematic review of the broader set of AI education literature, the bulk of which was published after 2000, revealed a set of six core AI competencies researchers had attempted to inculcate in learners: (1) recognizing AI, (2) understanding the features of intelligence, (3) recognizing that AI can be developed for a wide variety of technologies and disciplines, (4) being able to distinguish between general and narrow AI, (5) being able to identify AI's strengths and weaknesses, and (6) being able to imagine future applications of AI and their implications.[57] This review also derived 15 related design considerations that can be used to guide the design of AI education.[58] Noting the importance for the general public to have some understanding of the technologies underpinning much of modern life, a number of researchers have begun exploring how to engage young learners in AI literacy, recommending pedagogy that relies on embodied, culturally-relevant approaches to instruction.[59]

The Artificial Intelligence for K–12 initiative,[60] sponsored by the Association for the Advancement of Artificial Intelligence and the Computer Science Teachers Association, identified five "Big Ideas" concerning AI that they recommend for children to understand: (1) computers perceive the world using

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55 Ng, D. T. K., Leung, J. K. L., Chu, S. K. W., & Qiao, M. S. (2021). Conceptualizing AI literacy: An exploratory review. *Computers and Education: Artificial Intelligence, 2*, 100041. http://dx.doi.org/10.1016/j.caeai.2021.100041

56 Ibid.

57 Long, D., & Magerko, B. (2020). What is AI literacy? Competencies and design considerations. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems. Association for Computing Machinery, New York, NY, USA (pp. 1-16). https://dl.acm.org/doi/abs/10.1145/3313831.3376727

58 Ibid.

59 Yang, W. (2022). Artificial Intelligence education for young children: Why, what, and how in curriculum design and implementation. *Computers and Education: Artificial Intelligence, 3*, 100061. https://www.sciencedirect.com/science/article/pii/S2666920X22000169

60 https://ai4k12.org/

sensors, (2) computer-based agents maintain representations of the world and use them for reasoning, (3) computers can learn from data, (4) to interact naturally with humans, computers require many kinds of knowledge, and (5) AI can impact society in both positive and negative ways.[61] The initiative is in the process of developing these concepts into curriculum guidelines, which can be found along with a compendium of other resources (links to books, reports, competitions, curriculum materials, emerging state standards, software, online courses, and more.)[62] Given the recency of the topic in education, it is reasonable to expect the definition and pedagogical recommendations for AI literacy to continue to evolve.

Computational Literacy in Computer Science Education

Computer science is broadly defined as the understanding of the hardware, software, processes, and applications of computers. It includes programming but is more than simply "coding." At the same time, it also includes elements of computational thinking: a problem-solving approach that involves skills in decomposition, algorithmic thinking, abstraction, and automation. The overlap and distinction of these elements are critical in framing computational literacy within the current context of computer science education. While computer science as a subject is being increasingly offered as a high school course, embedding computational thinking across subjects continues to be a growing field of interest—particularly in developing computational literacy in early grade bands.

At the K-8 level, efforts to integrate computational thinking into existing courses, such as to STEM, English Language Arts, or English as a Second Language, can promote computational literacy. In particular, core competencies of abstraction, generalization, and debugging can be embedded into curricula by using block-based languages like *Scratch* and *Storytelling Alice*. Additionally, the NSF initiated the STEM+Computing (STEM+C) program (2014-2019) to catalyze research and development on the integration of computing and computational thinking in preK–12 STEM education. Projects like *Bootstrap* and *Project GUTS* provide resources for integrating computational literacy into middle school science and math classes.

In one of the largest moves to address the challenge of making high school computing coursework more engaging and accessible, the College Board developed the *Advanced Placement (AP) Computer Science Principles (CSP)* course and exam in 2017. The inaugural year of the AP CSP exam saw the largest launch in the College Board's 50-year history. In addition, an introductory high school course, *Exploring Computer Science (ECS),* expanded computational literacy opportunities to prepare students for more advanced computing courses. As part of expanding access to these courses, NSF funds projects that support curricula and teacher professional development opportunities for both ECS and CSP through the *Computer Science for All: Research and Research Practitioner Partnership* program. Many of the CSP courses endorsed by the College Board have been scaled through this program, including *Beauty and Joy of Computing, Mobile CSP, UTeachCS*, and *CSMatters*. In addition, organizations such as *Code.org*, the *National Math and Science Initiative*, *Project Lead the Way*, and the *Infosys Foundation USA* have also developed resources for ECS and CSP curricula.

Though the *Computer Science for All* effort and national attention on diversity, equity, and inclusion in computer science education have made strides in broadening participation, women, students of color, students from families with limited financial resources, students with disabilities, and students who live

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61 Touretzky, D., Gardner-McCune, C., Martin, F., & Seehorn, D. (2019). Envisioning AI for K-12: What Should Every Child Know about AI? *Proceedings of the AAAI Conference on Artificial Intelligence*, 33(01), 9795-9799: https://doi.org/10.1609/aaai.v33i01.33019795

62 https://ai4k12.org/

in rural communities remain underrepresented and underserved in computing. There has been an explosion of promising programs attempting to address these issues. For example, the *Aspire IT* program recognizes and supports the IT accomplishments of girls and *TECHNOLOchicas* showcases Latinas in technology. National organizations, like the *Boys and Girls Club of America, 4H, Code Interactive, Code2040, Black Girls Code*, and *Girls Who Code* have also adopted technology-related activities in the after-school space. In addition, the *Strategic Computer Science for All Planning Tool for School Districts* serves as a strategic resource for scalable and equitable course sequences to build computational literacy in states and districts.

Computational Literacy in Cybersecurity

The acceleration of technical progress in the digital era has made the use of devices and applications employing cloud computing, big data analysis, blockchains, and AI routine. The adoption and integration of advanced digital technologies such as 5G mobile networks, the internet of things (IoT), cloud computing, artificial intelligence, big data analysis, quantum, robotics, etc., make the convergence of telecommunications and information technologies viable and have created strong demand for workers who are capable of designing, developing, implementing, and maintaining defensive and offensive cybersecurity strategies. However, the convergence of dynamic and interconnected technologies makes it difficult to clearly describe the work required to design, build, secure, and implement these data, networks, and systems.

The convergence of technologies has made describing cybersecurity work and those who can perform the work a challenge. Compounding this problem, organizations use varying and conflicting definitions and often loosely use them interchangeably.

Cyber as a term, which is often used as a prefix, usually refers to things that have a relationship with modern technology, "referring to both information and communications networks."[63] The term cyberspace refers to a virtual space denoting connections between computers and often the networks, devices, data, control systems, etc., that reside or can be reached in that space.[64] Cybersecurity refers to protecting not just things that are in what is commonly thought of as cyberspace, but also things that might be separate, such as defense systems, cars, medical devices, and other applications that have a computational component that could be affected adversely.[65]

The National Initiative for Cybersecurity Education (NICE) Workforce Framework for Cybersecurity (NICE Framework), National Institute of Standards and Technology (NIST) Special Publication 800-181, provides employers, education and training providers, and learners with a set of building blocks for describing the tasks, knowledge, and skills (TKS) that are needed as the foundation for all individuals , in addition to those who may go on to perform cybersecurity work.[66] Through these building blocks, the NICE Framework enables students to develop skills, job seekers to demonstrate competencies, and employees to accomplish tasks. As a common and consistent lexicon that categorizes and describes cybersecurity tasks, the NICE Framework improves communication about how to identify, recruit, develop, and retain cybersecurity talent. The use of common terms and language also helps to organize

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63 NIST ITL Computer Resource Center. https://csrc.nist.gov/glossary

64 The Department of Defense defines cyberspace as a global domain within the information environment consisting of the interdependent network of information technology infrastructures and resident data, including the internet, telecommunications networks, computer systems, and embedded processors and controllers, https://sgp.fas.org/crs/natsec/IF10537.pdf

65 NIST ITL Computer Resource Center defines cybersecurity as the ability to protect or defend the use of cyberspace from cyberattacks, https://csrc.nist.gov/glossary

66 NICE Framework Resource Center, https://www.nist.gov/itl/applied-cybersecurity/nice/nice-framework-resource-center

and communicate the work to be done and the attributes of those that are qualified to perform that work. The NICE Framework data also provides a mapping to the employment codes as required by the Federal Cybersecurity Workforce Assessment Act.[67]

The widespread deployment of digital technologies throughout the nation and the ongoing shift to a knowledge-based economy have created strong demand for cybersecurity workers and is among the fastest growing and well-paying opportunities in our economy. This demand for highly skilled cybersecurity workers continues to grow.[68] Despite these facts, there is a significant shortage of cybersecurity workers.[69] This deficit is a significant risk to America's overall national security and economic prosperity. The inclusion of individuals from groups historically underrepresented in cybersecurity and other technology related disciplines creates the opportunity to expand the cybersecurity workforce. The need to prioritize upskilling, reskilling, and alternative career pathways from existing disciplines and targeting a wider range of demographics is needed to address the employee shortage.

The NICE framework recognizes that cybersecurity is not a monolithic entity. Cybersecurity folds into all disciplines; it is cross-cutting and multidisciplinary in nature. All students, no matter what their future education or career path, must understand core cybersecurity concepts and the impacts to be prepared for college, careers, and societal responsibilities. Computational literacy raises the baseline for all individuals to be knowledgeable and skilled with cybersecurity concepts that constrain and limit adversaries' activities. Examples of current federal cybersecurity programs can be found in Appendix 2.

Computational Literacy in Data Science

Data Science is often described as an inter-disciplinary field combining mathematics and statistics, computer programming, and domain knowledge to yield insight from data.[70] Researchers have also advocated data ethics and civic responsibility as a crucial component for data science education programs.[71] For educational contexts, approaches that resemble the scientific method and statistical practices to draw meaning from data have been integrated in some curriculum designs, constituting a "data cycle."[72] In distinguishing data science from traditional statistics or computer science education, researchers have also emphasized a focus on specialized automation for data analysis[73] and on the processes behind data generation, given both the analytical complexity and context-rich, digital sources inherent to modern data practice.[74]

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67 Workforce Planning for the Cybersecurity Workforce. Policy, Data, Oversight: Human Capital Management. https://www.opm.gov/policy-data-oversight/human-capital-management/cybersecurity/

68 For example, Bureau of Labor Statistics, U.S. Department of Labor, *Occupational Outlook Handbook*, Information Security Analysts, at https://www.bls.gov/ooh/computer-and-information-technology/information-security-analysts.htm

69 Cybersecurity Supply and Demand Heat Map, https://www.cyberseek.org/heatmap.html

70 National Academies of Sciences, Engineering, and Medicine. (2020). *Roundtable on Data Science Postsecondary Education: A Compilation of Meeting Highlights*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25804; IBM Cloud Learn Hub, Data Science. 2020. https://www.ibm.com/cloud/learn/data-science-introduction

71 Schanzer, E., Pfenning, N., Denny, F., Dooman., S, Politz, J., Lerner, B., Fisler, K., & Krishnamurthi, S. (2022). Integrated Data Science for Secondary Schools: Design and Assessment of a Curriculum. *Proceedings of the 53rd ACM Technical Symposium on Computer Science Education* V. 1 (SIGCSE 2022), March 3– 5, 2022, Providence, RI, USA. ACM, New York, NY, USA. https://doi.org/10.1145/3478431.3499311

72 Gould, R., (2021). Toward data-scientific thinking. *Teacher Statistics,* 43, S11-S22. https://doi.org/10.1111/test.12267

73 National Center for Education Research. (2022). *Catalyzing a New Field: Data Science in K-12 Education.* https://ies.ed.gov/ncer/whatsnew/techworkinggroup/pdf/DataScienceTWG.pdf

74 Makar, K., & Rubin, A. (2009). A Framework for Thinking about Informal Statistical Inference. *Statistics Education Research Journal*. 8(1), 82-105. https://iase-web.org/documents/SERJ/SERJ8(1)_Makar_Rubin.pdf?1402525008

The Bureau of Labor Statistics employment projections expect at least 700,000 in net job gains in computer and mathematics sectors over the next decade, and designates data science as "much faster than average" growth by 2030.[75] The share of global companies planning to adopt "big data" analytics only further increased during COVID, while nearly half of companies planned to reduce their traditional workforce due to automation. Most critically, a National Academies of Sciences, Engineering, and Medicine roundtable noted that early exposure to data science in K–12 contexts may be a critical lever for expanding access and diversifying participation in the professional data science field.[76]

Moreover, these effects are widespread and not just limited to the technology industry—data analytics is now commonplace for quality control in manufacturing, for nurses querying patient data, and for farmers maximizing yields or managing climate risks. While the number of people with formal jobs as "data scientists" will significantly increase, the jobs requiring relatively intensive data analysis skill sets continues to grow exponentially, with LinkedIn research noting that "analytical and data-centered hard skills continue to reign supreme" for all job-seekers over the next decade.[77] In short, all students will need to learn at least some data science or may find themselves significantly unprepared for today's careers and tomorrow's workplace.

Beyond the labor market, data science is increasingly needed for daily life. Whether navigating social media, planning personal finances, or making personal health decisions, the amount of data now regularly consumed by the general public has exploded. Moreover, early evidence suggests classroom instruction emphasizing community-based learning, computational thinking, and relevant, local data has potential to re-engage students and leapfrog learning losses. Research examining the integration of data science activities embedded in other school subjects also demonstrate the potential to increase student engagement and teacher performance concurrently.[78] In response to these changes, other countries (including China, South Korea, Germany, Scotland, and New Zealand) have already incorporated data science opportunities in secondary education. Achieving national data literacy—and by extension, ensuring all our students are data literate by high school graduation—will be a critical step for building economic and social resiliency for the 21st century, and contribute to our national competitiveness.

While a distinct field, data science can serve as a promising strategy to pursue computational literacy in K–12 contexts. Researchers and practitioners have posited that data science education programs require a "thorough blending" of computational thinking and inferential or statistical thinking.[79] A data science program may incorporate significant components of computational literacy to accomplish its own focus on teaching modern data analytics, and as a result, develop students who are "literate" in reading, working with, and communicating about data. Moreover, the convergence of these disciplines in the real-world suggest the need for creative approaches to incorporate data science into other

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75 Bureau of Labor Statistics, U.S. Department of Labor, *Occupational Outlook Handbook*, Data Scientists, at https://www.bls.gov/ooh/math/data-scientists.htm

76 National Academies of Sciences, Engineering, and Medicine. *Roundtable on Data Science Postsecondary Education: A Compilation of Meeting Highlights*.

77 LinkedIn. New LinkedIn Research: Upskill Your Employees with the Skills Companies Need Most in 2020. https://www.linkedin.com/business/learning/blog/learning-and-development/most-in-demand-skills-2020

78 Erwin, R. (2015). Data Literacy: Real-World Learning Through Problem-Solving With Data Sets. *American Secondary Education*, 43(2), 18-26. https://www.jstor.org/stable/43694208?seq=4

79 Jordan, M. (2018). On Computational Thinking, Inferential Thinking, and Data Science. https://stat.tamu.edu/big-data-modeling-conf/jordan-abstr/; Gould, R., Toward data-scientific thinking.

subjects,[80] with some K–12 data science programs having already pursued customized, modular integration into physical and life sciences, social studies, and the humanities.[81] Data science content may be an especially concrete way to integrate computational literacy components throughout K–12, with subject-relevant datasets (biology lab data, history timeseries data) and techniques (data modelling, data visualization) providing an engaging vehicle to teach other required content standards, and as a result contribute to a student's overall computational literacy. A more detailed overview of data science learning frameworks and practices can be found in Appendix 3.

Computational Literacy in Digital Literacy

Computer literacy, digital fluency, media literacy, information and communication technology literacy (ICT), and digital citizenship are just a few of the many terms used to describe the productive and responsible use of technology online. Digital literacy skills enable an individual to use computers, software applications, databases, and other technologies safely and ethically to achieve a wide variety of academic, work-related, and personal goals.

Digital literacy education often falls to the media specialists, who offer stand-alone instruction on everything from internet safety to proper computer use to evaluating information sources. However, research reveals that content needs to be included in the curriculum in all classes and not just provided as a stand-alone lesson or topic. Content impacts almost every subject, and integration needs to occur as a partnership among classroom teachers, librarians, technology specialists, and students, and continue beyond the K–12 setting. Curricular integration also influences and impacts student-centered teaching methods as problem-based learning, evidence-based learning, and inquiry learning. Digital literacy also helps individuals develop a metacognitive approach to learning, making them conscious of the explicit skills required for gathering, analyzing, and using information. This integrated approach becomes increasingly important as additional topics and skill sets become critical.

After the educational community pivoted to a virtual format due to COVID-19, there was an increasing awareness of the need for skill sets to both instruct and learn in an online platform. These unexpected changes also sparked an uptick in malevolent actors devising methods to breach virtual education spaces, highlighting the need for cybersecurity awareness and practices in all digital literacy instruction sessions and exercises.

As the education sector and the economy overall face ongoing financial challenges because of the pandemic, the need for administrators, teachers, librarians, and learners to collaborate has never been greater. Librarians can provide direct instruction and remain very capable of delivering digital literacy content support in content areas where newer technology tools can challenge those colleagues requiring additional help. Librarians offer critical and insightful input for sequential learning modules and help develop robust curriculum addressing existing media and educational technology standards. The American Association of School Librarians[82] offers crosswalks between the National School Library Standards[83] and other sets of national teaching and learning standards, such as *Future Ready* and Next

[80] Horton, N., & Hardin, S. (2021). Integrating Computing in the Statistics and Data Science Curriculum: Creative Structures, Novel Skills and Habits, and Ways to Teach Computational Thinking. *Journal of Statistics and Data Science Education*, 29:sup1, S1-S3. https://doi.org/10.1080/10691898.2020.1870416

[81] Schanzer, E. Integrated Data Science for Secondary Schools: Design and Assessment of a Curriculum.

[82] https://www.ala.org/aasl/

[83] https://standards.aasl.org/

Generation Science Standards,[84] and the International Society for Technology in Education Standards for Students and Educators.[85] While students are taught to employ effective research strategies, librarians must also provide alternative ways students can demonstrate competency and progress in their use of technology and digital resources. Students are often required to choose reliable sources and explain why a source is valid, often referred to as information literacy. This skill set can also apply to mis- and disinformation, edited social media sources, fraudulent emails, and other spamming and social engineering encounters. Evaluating sources and demonstrating the ability to identify and differentiate reliable information and resources from those that are potentially harmful are valuable competencies. In addition, education on good digital citizenship and identifying and responding to cyberbullying behaviors are needed skills.

With increased administrative support, media specialist and librarians will be well equipped to offer computational literacy instruction and seamlessly weave the important topics and concepts into instruction sessions. When taught well, students leave the K–12 environment with a strong sense of digital literacy knowledge, social responsibility, and an enduring interest in protecting their communities and the world.

Individuals of all ages are also faced with a wide variety of information choices in their academic studies, their workplace, and in their personal lives. This information often comes to individuals in unfiltered formats, raising questions about its authenticity, validity, and reliability. The Information Literacy Competency Standards for Higher Education[86] have brought information literacy to the forefront of the higher education conversation by defining information literacy as a set of abilities requiring individuals to "recognize when information is needed and have the ability to locate, evaluate, and use effectively the needed information."[87] The Information Literacy Competency Standards for Higher Education provides a framework for assessing the information literate individual. It also "extends the work of the American Association of School Librarians Task Force on Information Literacy Standards, thereby providing higher education an opportunity to articulate its information literacy competencies with those of K–12 so that a continuum of expectations develops for students at all levels." Computational literacy encompasses digital literacy and information literacy and initiates, sustains, and extends lifelong learning through the knowledge and skills that are necessary to engage with technologies.

Computational Literacy in Science and Engineering

The *Advancing Excellence in P-12 Engineering Education* project[88] identified computational thinking as a core engineering concept to create a foundation for students to conduct the quantitative analyses that engineers and related professionals perform. Similarly, the National Academies for Science, Engineering and Medicine Committee for the Workshops on Computational Thinking contends that computational thinking is necessary to develop efficient and automated physical design solutions,

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84 https://www.nextgenscience.org/

85 https://www.iste.org/

86 Association of College and Research Libraries. (2000). Information Literacy Competency Standards for Higher Education. Association of College & Research Libraries. https://alair.ala.org/bitstream/handle/11213/7668/ACRL%20Information%20Literacy%20Competency%20Standards%20for%20Higher%20Education.pdf?sequence=1

87 Association of College and Research Libraries. (1989). Presidential Committee on Information Literacy: Final Report. American Library Association. https://www.ala.org/acrl/publications/whitepapers/presidential

88 https://www.p12engineering.org/

visualizations of design concepts, and computational scientific models. These abilities, which also include thinking critically about complex problems, generating creative solutions, and communicating solutions effectively, are now considered necessary at all levels of scholarship.[89]

The rise of engineering in K–12 education embodies the notion that the application of content knowledge and practice skills increases student engagement and knowledge retention. Providing students with situational or real-world contexts, and science and engineering design challenges offer students the opportunity to envision how and why the scientific theories and mathematical formulas they are expected to learn are relevant to their world. Some educators are using engineering design activities and lessons to facilitate computational literacy for their students in and out of the classroom.

The fundamental engineering design strategies align well with STEM instruction because of the relationship with the STEM skills of modeling, reasoning, and problem solving,[90] all components of computational literacy. These engineering concepts are identified in the Next Generation Science Standards and are recognized as key scientific practices, which should be integrated into K–12 classrooms.

As science and engineering skills and concepts gain attention in K–12 education, informal learning institutions like museums and science centers are doing their part by designing exhibits and experiences to promote engineering strategies. Some reports suggest that computational and engineering thinking can empower each other, and engineering design can be an appropriate context for developing children's problem-solving skills. Using a family-based engineering design activity at a small science center exhibit, researchers were able to link some computational thinking competencies with the student's engagement in an engineering design activity.[91]

The emphasis on coding in K–12 schools, which is typically taught by technology and engineering (T&E) educators, has expanded to include computational literacy. Integrated STEM education encourages the adoption of math and science to solve engineering problems and T&E educators can further incorporate computing skills to solve problems.

Many unplugged engineering design challenges allow educators to convey computational literacy components through engaging games and puzzles using simple algorithms. Students can apply mathematics and scientific knowledge to design their engineering design solution and use the computational literacy elements and computational thinking approach to accurately predict the outcome of their solution.[92]

The Next Generation Science Standards includes computation thinking among its eight science and engineering practices. One example includes a sequence of instructional activities focusing on groundwater contamination, a popular science topic. Students use spreadsheets to manage data,

[89] Strimel, G. J., Morehouse, A., Bartholomew, S. R., Swift, C., & Woessner, J. (2019). integrating computational thinking through wearable technologies and programmable e-textiles. *Technology and Engineering Teacher*, 78(8), 16-19. https://scholarsarchive.byu.edu/facpub/5562

[90] Sengupta, P., Kinnebrew, J. S., Basu, S., Biswas, G., & Clark, D. (2013). "Integrating computational thinking with K-12 science education using agent-based computation: A theoretical framework." *Education and Information Technologies*, 18(2), 351–380. https://dl.acm.org/doi/10.1007/s10639-012-9240-x

[91] Ehsan, H., Rehmat, A. P., & Cardella, M. E. (2021). Computational thinking embedded in engineering design: capturing computational thinking of children in an informal engineering design activity. *International Journal of Technology and Design Education*, 31(3), 441-464. https://doi.org/10.1007/s10798-020-09562-5

[92] Sung, E. (2019). Fostering computational thinking in technology and engineering education: An unplugged hands-on engineering design approach. *Technology and Engineering Teacher*. 78(5). 8-13. https://eric.ed.gov/?id=EJ1203698

visualization and simulation tools to explore phenomena, and build computational models to design pollution control solutions and other problems they might experience in their community, all examples of computational literacy components.[93]

Drones or quadcopters have been used for integrating, teaching, and improving programming, coding, and analytical thinking skills. The design, use, and integration of these devices can introduce and assist students in a wide variety of subjects from science, dynamics, and technology to electronics, engineering design, and mathematics.[94]

Another approach to create effective learning environments to incorporate problem solving strategies within the science and engineering disciplines is the implementation of computational model-building activities that are grounded in productive failure. Throughout the building of the model, students apply skills, including abstraction, algorithmic thinking, evaluation, generalization, and decomposition. This effort shows how building computational models, can allow for students to practice computational literacy and for educators to incorporate these key practices into their science and engineering classrooms.[95, 96]

Several engineering curricula initiatives have recently embedded computational literacy and data science in their efforts. For instance, the research-based *Engineering is Elementary*[97] curricula developed by the Museum of Science in Boston, offers Engineering and Computer Essentials.[98] There are currently 5 units, one for each grade 1–5, that address programming robots, creating animations, building automated systems, designing computer games, and analyzing digital images, respectively. Each unit also aligns with corresponding math extensions.

Project Lead the Way started as a high school engineering curricula and has expanded to elementary and middle grades. Curricula teaches students that real-world problems often have multiple solutions with many pathways to achieve success. Environmental sustainability, civil engineering and architecture, digital electronics, and aerospace engineering, are just a few of the courses available for students to explore possibilities. Content encourages students to adopt a problem-solving mindset, engaging them in compelling, real-world challenges that help them become better collaborators and thinkers.

The Smithsonian Science for Computational Thinking program[99] provides instructional units that integrate computational thinking into the science classroom, thereby promoting transdisciplinary learning and convergence education. There are currently two units, covering grades 3 and 5 that address developing and using models; using patterns and data analysis to support the design of solutions; and obtaining, evaluating, and communicating information.

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93 Gunckel, K. L., Covitt, B. A., Love, G., Cooper-Wagoner, J. A., & Moreno, D. (2022). Unplugged to Plugged In. *The Science Teacher*, 89(3): https://www.nsta.org/science-teacher/science-teacher-januaryfebruary-2022/unplugged-plugged

94 Bartholomew, S. R., Zhang, L., & Weitlauf, J. (2018). Engineering design and coding through quadcopters. *Technology and Engineering Teacher*, 78(1), 14-21. https://eric.ed.gov/?id=EJ1190262

95 Lyon, J. A., & Magana, A. J. (2021). The use of engineering model-building activities to elicit computational thinking: A design-based research study. *Journal of Engineering Education*, *110*(1), 184-206. https://doi.org/10.1002/jee.20372

96 National Science Teaching Association (n.d.). Science and Engineering Practices: Using Mathematics and Computational Thinking. https://ngss.nsta.org/Practices.aspx?id=5

97 https://eie.org/research

98 https://eie.org/stem-curricula/computer-science

99 https://ssec.si.edu/computational-thinking

As more tools and approaches are developed, researched, and assessed, teachers and students will have more options to grow their own knowledge and comfort levels in developing computational literacy skills and competencies applied to engineering.

Computational Literacy in Advanced Manufacturing

The manufacturing sector is transforming toward digital formats that require novel upskilling and instrument awareness. This shift in manufacturing is part of the Industry 4.0 movement which integrates "smart" technologies that require unique computational literacy skills to manage internet of Things (IoT), cloud computing and analytics, AI and machine learning, and autonomous systems. Although there remains some disagreement, most evidence suggests that automation, AI, and robotics will yield a net worldwide increase of manufacturing jobs over the coming decade.[100]

While the rise of industrial technology will allow humans to work alongside machines in a progressively productive manner, these same technologies in advanced manufacturing will require a highly skilled and knowledgeable workforce. The National Association of Manufacturers estimates that the United States could have more than two million unfilled manufacturing jobs by 2030.[101] Therefore, a renewed investment in workers is needed, including building computational literacy in all STEM levels, K–12 through post-graduate degrees, and technical training programs with industry-recognized credentials, apprenticeships and internships, and other work-based experiences.

These technologies should be developed and deployed in a way that complements workers' skills, rather than substituting for them. To build a robust advanced manufacturing industry with high quality jobs, the manufacturing workforce must focus particular emphasis on including individuals from backgrounds historically underrepresented in STEM fields and develop the skills of its workers with agile education and training systems that keep pace with innovation. Education and workforce development programs must also be capable of responding with agility to the changing mix of skills and competencies needed for advanced manufacturing. Pedagogy must continue to explore new techniques and delivery systems. This means developing and making more widely available sector partnership training programs, to include engaging distance learning and virtual simulations. Educators and students must be well-versed in computational literacy skills to take full advantage of these strategies. Examples of current federal manufacturing programs can be found in Appendix 4.

Computational Literacy in Quantum Information Science

Quantum Information Science (QIS), the intersection of quantum mechanics and information science, will change the way we process, transmit, and secure data. Much like the scientific and educational developments that made classical computing an industrial turning point, quantum science has the potential to advance the fields such as computing, cryptography, and communications. Additionally, advances in quantum computing could help the broader STEM community answer fundamental questions in physics, chemistry, biology, and materials sciences, and bolster the utility of artificial intelligence.

A key element to U.S. goals in QIS is a strong workforce pipeline. Accordingly, workforce growth is a pillar of the U.S. quantum strategy,[102] and subsequent NSTC reports continue to emphasize the

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100 https://www.whitehouse.gov/wp-content/uploads/2022/10/National-Strategy-for-Advanced-Manufacturing-10072022.pdf

101 https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/24/the-biden-harris-plan-to-revitalize-american-manufacturing-and-secure-critical-supply-chains-in-2022/

102 https://www.quantum.gov/wp-content/uploads/2020/10/2018_NSTC_National_Strategic_Overview_QIS.pdf

importance of workforce development and set policy goals for the United States in this space.[103] Collectively, these various strategies indicate the need for the United States to strengthen and evolve its domestic quantum workforce pathways and also continue to attract and retain international talent.[104] Quantum technology relies on the unique properties of quantum mechanics specifically the sub-atomic particles of the natural world. It is the observation of these natural phenomena (the quantum state) that enable an alternative to classical computing. In classical computing, information is organized in “bits” with an on or off state that allows for broader computation to occur. In quantum technology, information is organized in a “qubit” which can have many states, thus solving one of the inherent obstacles in classical computing. This is accomplished via the encoding and observation of a physical element.

The context for quantum technology is very different from that of classical computing in this regard, requiring different mental models and education skillsets. For our society to embrace and benefit from this technology, a new approach to learning will be required. A 2022 workshop[105] between the Harvard University Center for Integrated Quantum Materials, the NSF, and OSTP arrived at nine key concepts of which all QIS learners should be aware.[106] A more detailed overview of the nine key concepts can be found in Appendix 5.

Holistically thinking about QIS education from the K–12 level up is critical to building national competency and innovation in QIS. Children in K–12 should be introduced to basic QIS topics and encouraged to pursue more advanced curriculum, thus, creating a pipeline to higher education.

Even more fundamentally, an understanding of computational literacy is an essential instructional piece at the intersection of multiple disciplines. Components of computational literacy form the basis for multiple paths of learning and are essential for success in 21st century careers like QIS.

Computational Literacy Definition Examples

The IWGCL definition of “Computational Literacy” is intended for use in federal solicitations for activities and reporting of programs that include support of or engagement with computational literacy in STEM education. Agencies are encouraged to use this definition in their programs and activities that support computational literacy in STEM education at all levels and in both school and out of school STEM activities. Increased computational literacy in STEM education has the potential to provide greater diversity, equity, and access to competitive careers of the future in the service of the nation and to the benefit of society. Below are examples of how the definition may be used by federal agencies. These examples are existing and are not exhaustive.

Federal Grant Solicitation and Selection Criteria

An agency may choose to require an applicant to describe the computational literacy components in STEM education programs or how the applicant intends to develop or include computational literacy in the implementation of the grant. Agencies may also require an applicant to describe the effective uses and successful methods for teaching computational literacy at specific levels. Depending on the objective of the grant, an agency may choose to require an applicant to identify computational literacy

[103] https://www.quantum.gov/strategy/#STRATEGY-DOCUMENTS
[104] https://www.quantum.gov/wp-content/uploads/2022/02/QIST-Natl-Workforce-Plan.pdf
[105] https://www.seas.harvard.edu/news/2020/05/teaching-next-generation-quantum-scientists
[106] https://files.webservices.illinois.edu/9156/keyconceptsforfutureqislearners5-20.pdf

as an absolute or competitive priority. An agency may also list computational literacy as an area of needed research to encourage applications in this area for a particular funding opportunity.

Department of Defense (DoD) Example: Funding opportunity HQ0034-21-S-F001 explicitly encouraged projects that improve the capacity of education systems and communities to create impactful STEM educational experiences for students and teachers and prepare the 21st century technical workforce. Funded projects aligned with the Federal STEM Education Strategy's vision of high-quality STEM education and the United States will be the global leader in STEM literacy, innovation, and employment. This consists of strategic partnerships, convergence, and building computational literacy, aligns with DoD STEM's mission, and promotes STEM literacy, innovation, and employment.[107]

Institute of Education Sciences (IES) Example: Federal agencies can include example research areas in discretionary grant solicitations to support computational literacy. The Department of Education's National Center for Education Research (NCER) in the Institute of Education Sciences (IES) releases an annual Request for Applications (RFA) for discretionary grant funding under the Education Research Grants Program (ALN 84.305A). The solicitation includes several examples of research that have the potential to lead to important advances in STEM education research on how computational literacy, data literacy, and data science can best be incorporated into STEM and other subject areas.

Agency Program Development and Planning

An agency, department, or program may choose to prioritize computational literacy in the development of their strategic plan, implementation plan, or project development.

NIST Example: The National K12 Cybersecurity Education Roadmap, developed by the National Initiative for Cybersecurity Education (NICE) Program Office within the National Institute of Standards and Technology (NIST), establishes a coordinated, coherent portfolio of K–12 cybersecurity education activities so that efforts and assets are deployed effectively and efficiently for greatest potential impact. One Roadmap goal, "Engage Students Where Disciplines Converge," identifies, designs, and shares cybersecurity resources for the future STEM and cybersecurity workforce. One objective under this goal "assists in building computational literacy by infusing cybersecurity concepts aligned to the NICE Framework into formal and informal instruction focusing on the holistic convergence of educational disciplines."[108]

STEM Engagement and Training

An agency, department, or program may choose to prioritize computational literacy in their STEM education and training opportunities.

NITRD Example: The Networking and Information Technology Research and Development (NITRD) Program hosts a STEM portal which offers a searchable database of federal STEM opportunities

[107] https://dodstem.us/

[108] NSF defines convergence as the deep integration of knowledge, techniques, and expertise from multiple fields to form new and expanded solutions for addressing scientific and societal challenges and opportunities. Convergence refers to not only the convergence of expertise across disciplines, but also the convergence of academic, government, and industry stakeholders to support scientific investigations and enable rapid translation of the resulting advances. Convergence integrates knowledge, methods, tools, and ways of thinking from multiple disciplines to form a comprehensive means to tackling scientific and societal challenges that exist at the interfaces of multiple fields.

including each programs description, link, and contact information.[109] The listed opportunities are generally focused on computational literacy related opportunities, but include many other STEM fields, since federal agency STEM programs are typically broadly defined. As agencies begin to use the computational literacy definition above, the NITRD STEM Portal can also be used to track the use of the term in STEM education and workforce development-related programs.

Addressing the Barriers to Computational Literacy

The digital connectivity that has brought economic growth and technological dominance has wholly transformed our society. A computationally literate society is necessary to drive exploration and scientific discovery, promote innovation and competitiveness, and create the conditions for building a workforce that can find new solutions for pressing challenges, enhance national security, promote economic prosperity, and provide good-paying jobs to improve American's quality of life.

Request for Information (RFI) respondents suggested ways to address the reported barriers (Appendix 1). Four key concept themes emerged to consider when integrating computational literacy into STEM education at all levels.

Fundamental Digital Skills	• Promote digital literacy skills (e.g., typing, cyber safety, coding) starting with our youngest learners, by creating opportunities for increased exposure (e.g., coding/cyber day, competitions, after school programs, student clubs) • Develop accessible tools for students with disabilities to engage in computational literacy activities (e.g., in data visualization, data analysis, and coding.) This is especially needed for students and the STEM workforce who are visually impaired
Teacher Professional Development	• Increase CL professional development initiatives for which educators are compensated • Incorporate cognitive concepts (e.g., decomposition, abstraction, pattern recognition, and algorithmic thinking) in CL learning goals • Create opportunities to apply the practices and technologies cited in the RFI, which can support teaching CL as a core competency • Employ content creators in generating meaningful integration resources for course support
Ethics	• Ensure that ethical use is integrated as a CL learning goal • Develop educational materials for cyber safety and best practices in online behaviors beginning in elementary school through post-graduate
Community Outreach	• Educate on the scope of CL concepts with more hands-on activities through schools and community organizations • Develop campaigns on applications of CL and technologies for a safer and more secure and efficient world • Promote CL self-efficacy and career awareness (e.g., through partnerships with industry and professionals in related fields), so that participants can see themselves as future global technology leaders and innovators

Image 2: Four concepts to integrate computational literacy in STEM education compiled from RFI respondents

The concepts in Image 2 serve to provide a holistic construction of the integration of computational literacy in STEM education as compiled from RFI respondents. Students, teachers, and the community

109 https://www.nitrd.gov/stem4all/

must all be guided toward a better understanding, and all must approach computational literacy in an ethical manner.

Recommendations

The Computational Literacy IWG considered these suggestions, along with ideas culled from an extensive literature review and discussions with numerous emerging technology federal partner efforts and developed the following recommendations for building computational literacy in STEM education, while also recognizing that different disciplines will determine how computational literacy best serves them as viewed through each federal agency's lens:

- ✓ Use the definition of computational literacy to help explain the complexity of components, strengthen agencies' ability to communicate consistently and clearly and create a society that can actively participate in the global digital economy and prepare for the workforce that is increasingly requesting a broader and more advanced set of digital and cognitive skills.
- ✓ Increase educator professional development initiatives that integrate computational literacy components applicable to their specific subject matter and grade level.
- ✓ Identify barriers to access and develop strategies to increase broadband services to all locations regardless of density levels, from small towns to urban neighborhoods, and among demographic groups of all races, educational attainments, and income.
- ✓ Advocate for tools and applications that demonstrate computational literacy components that are accessible to all.
- ✓ Promote computational literacy as a means for multiple pathways to STEM academic and career options leading to high-demand and good-paying jobs for Americans.
- ✓ Encourage Tribal, State, Local Education Agencies, Institutes for Higher Education, and training providers to use consistent language in professional development programs, in their use of industry certifications and academic credentials, and in their selection of relevant training opportunities for their workforce and develop training opportunities that incorporate computational literacy content and instruction.
- ✓ Support campaigns that highlight the scope of computational literacy components and the need for building a computational literate society.
- ✓ Engage community-based organizations, parent associations, guidance counselors, and other stakeholders who support student course-taking decisions and career awareness in outreach activities highlighting the importance of computational literacy.
- ✓ Promote development of computational literacy content that embraces the transdisciplinary and convergence of STEM education.

Conclusion

Building computational literacy in STEM education at all levels will require the use of a common definition of computational literacy, particularly within the context of the growing STEM landscape; equitable access, including sufficient broadband, that transcends geography, race, socioeconomic status, disability status, and learning challenges; content that highlights current and emerging advanced technology and cognitive skills, and professional development around computational literacy and the pedagogical delivery methods to take advantage of the educational technology for learning, work, and everyday life.

This document provides a common lexicon to help agencies and stakeholders understand the components of computational literacy, highlights the need for computational literacy to engage in high-demand and well-paying jobs, and shares best practices to address current barriers, to include significant investment to scale computational literacy opportunities and create equitable access for all students, regardless of state, district, or zip code.

Appendix 1 Summary Analysis from FC-STEM Request for Information (RFI): Computational Literacy Analysis

In Fall 2020, a public request for information (RFI) was released to support the implementation of the Federal STEM Education Strategic Plan, and to better understand the impacts of the COVID-19 pandemic on learners and educational institutions.[110] Responses to RFI questions related to computational literacy were analyzed and coded into emerging themes. There were 115 respondents with varied backgrounds including teachers, state government employees, students, university and community college faculty, education-based non-profits, federally funded programs, for-profit organizations, and federal agencies.

The **goals for the Computational Literacy Interagency Working Group** on this RFI were to identify:

- **Benefits & challenges** when integrating computational literacy within a STEM curriculum
- **Key concepts** to be considered for integration into all levels of STEM education
- **Existing programs, content, and curriculum** examples of building computational literacy in STEM education
- **Technologies and resources** that are currently being used in STEM education

Responses to RFI questions related to computational literacy were analyzed and coded into emerging themes. There were 115 respondents with varied backgrounds including teaching, state governments, students, universities, community college, education-based non-profits, federally funded programs, for-profit organizations, and federal agencies.

I. Computational literacy fields of study cited in the RFI

- Machine Learning
- Data Science & Visualization
- Computer Science
- Quantum
- Artificial Intelligence
- Internet of Things
- Cybersecurity
- Digital literacy/digital citizenship
- Manufacturing
- Engineering

II. Perceived benefits of integrating computational literacy within a STEM curriculum

Convergence Learning

- Broadens the scope of mathematics (e.g., statistics, informatics, modeling)
- Promotes data science for all STEM disciplines
- Real world examples of how CS is applicable may interest more students versus pure coding/CS courses

[110] Notice of Request for Information on STEM Education.

- Digital tools that can overlap across math, science, and English language
- Versatility of computational literacy, coding, numerical modeling can introduce diverse fields (e.g., crime fighting, military operations, space travel, manufacturing, and climate science)

Fosters Equity

- Increases access: Integrating computational literacy into STEM curricula means that students in a variety of different subjects would have access to computational literacy concepts
- Evens the playing field: Less reliance on academic selectivity or resource availability
- Inclusive of all groups: reaches traditionally underserved communities and connects computational literacy to personal issues across subjects
- Modernizes science education: computational literacy in STEM education is needed to accurately reflect how computers, algorithms, social networks etc., are currently thinking and operating
- Application of technology for a safer and more secure world and allows students to see themselves as future global technology leaders and innovators

Builds Problem Solving Skills

- Include computational thinking (problem representation, decomposition, abstraction, simulation, verification, prediction) allows students to make sense of problems and persevere in analyzing/interpreting data, and communicating solutions to problems
- Less emphasis on memorization: creates opportunities for deeper understanding, problem-solving, mathematical modeling.
- Comprehend complex problems in STEM fields and develop possible solutions using computing
- Next Generation Science Standards describe "strategies for organizing and searching data, creating sequences of steps called algorithms, and using and developing new simulations of natural and designed systems."
- Innovation and Technology Skills: will be necessary to develop and work with Future Technologies

III. Potential Challenges When Integrating Aspects of Computational Literacy into Instructional Delivery

Misconceptions

- Interpretations included a wide range of skill sets and topics.
- Computer science exclusivity: Siloed thinking that computational literacy means CS only or must require advanced levels of technology.
- Lack of appreciation for the wide range of computational skills including software development, data visualization, statistics, machine learning, ethics, safety, cybersecurity, and working with large computational infrastructure

Instructor Experience

- Lack of expertise in instructors: Most teachers have not been formally training in computational literacy, or in curriculum integration

- Ineffective implementation: Superficial integration can leave students without the depth of experience necessary to develop computational literacy
- Limited application of technology: Tech used mainly for simulations; coding in a vacuum; no real-world or hands-on elements

State Education Policies

- Integrating computational literacy is considered a secondary priority to traditional subjects
- Lack of funding and accountability for districts to do implementation work
- Insufficient depth of implementation: computational literacy in afterschool programs is restricted to a sample of students; not embedded in the curriculum

IV. Key Concepts to Consider When Integrating Computational Literacy into STEM Education at All Levels

- Fundamental skills - Increase digital literacy and awareness in the youngest learners, K–5, within basic computer competencies (e.g., typing, safety)
- Ethics - Data ethics, cyber safety: In middle school we should cover cyberbullying, best practices in online safety, etc.
- Teacher professional development - Teacher training in computational literacy: Interweaving core subject learning and computational thinking requires in-depth of knowledge in both fields of study
- Cognitive thinking - Cognitive concepts (e.g., decomposition, abstraction, pattern recognition, and algorithmic thinking) should be the focus of computational literacy

V. Existing Programs, Content, Curriculum, or Education and Training Opportunities That Inform Successful Examples of Building Computational Literacy in STEM Education

- Live Online Learning applications for collaboration and video call. Cited applications included Zoom, Teams, WebEx, Google Suite
- Hackathons and Competitions; collaborative and competitive computer programming
- Outreach Programs (e.g., K–12 afterschool, computer technology workshops and camps, Makerspaces)
- Educator Professional Development and accommodations and opportunities for technology training, and space and time to redesign curriculum
- Curriculum Integration, lesson planning and software applications embedded in course work; Data Science in the Math curriculum, transdisciplinary projects that utilize computational literacy

VI. Technologies and Resources Currently Used and Cited

- Data & Computational Tools (e.g., software languages) and programs for productivity (e.g., Python, Rstudio, Excel, Google Sheets, GIS, Jupyter, Notebooks)
- Learning Management Systems, such as software application for the administration and delivery of educational courses (e.g., Canvas, Google Classroom, Moodle, Schoology, Blackboard)
- Content Sharing platforms/applications to distribute content virtually (e.g., Youtube, Facebook/Instagram Live, GitHub)

- Specialized hardware for small classroom for coding, data collection, engineering (e.g., UBTech, Sphero/mini-spheros, Ozobots, Lego WeDo 2.0, Finch robots)
- Online Learning Platforms that foster remote instruction, asynchronous, learning supplement (e.g., Khan Academy, Code.org, My Open Math, Pivot Interactives, MIT App Inventor)
- Educational Productivity online tools/applications for student collaboration (e.g., Desmos, Jamboard, Pear-deck, Screencastify, Stop-Motion, WeVideo, Vernier Graphical Analysis)

VII. Recommendations for Successful Integration of Computational Literacy in STEM Education Based on RFI Responses

Fundamental Digital Skills

- Promote digital literacy skills (e.g., typing, cyber safety, coding) starting with our youngest learners, by creating opportunities for increased exposure (e.g., coding/cyber day, competitions, after school programs, student clubs)
- Increase computational literacy professional development initiatives for which educators are compensated

Curriculum Integration

- Incorporate cognitive concepts (e.g., decomposition, abstraction, pattern recognition, and algorithmic thinking) in computational literacy learning goals
- Create opportunities to apply the practices and technologies cited in the RFI, which can support teaching computational literacy as a core competency
- Employ content creators in generating meaningful integration resources for course support

Cyber Ethics

- Ensure that ethical use is integrated as a computational literacy learning goal
- Develop educational materials for cyber safety and best practices in online behaviors beginning in elementary school through post-graduate

Community Outreach

- Educate on the scope of computational literacy concepts with more hands-on activities through schools and community organizations
- Develop campaigns on applications of computational literacy and technologies for a safer and more secure and efficient world
- Promote computational literacy self-efficacy and career awareness (e.g., through partnerships with industry and professionals in related fields), so that participants can see themselves as future global technology leaders and innovators

Public responses were received from the *Request for Information on STEM Education*[111] regarding components, key concepts, and/or topics to be included in efforts to build computational literacy in STEM education, as follows:

- Computational literacy components should include data literacy, data science, computational thinking, coding, computing, computer-based modeling, cyber and data ethics, cybersecurity, cyber safety.
- Components may be dependent on the age of the learner. For example, the youngest learners in K–5 need more focus on digital skill building such as keyboarding and proper computer/mobile device use. Middle school learners may need to learn about cyberbullying, online safety.
- In educational contexts, some are calling for computational thinking to be reframed as *computational participation*, emphasizing “the ability to solve problems with others, design systems for and with others, and draw on computer science concepts, practices, and perspectives” so that learners are able to meaningfully participate as critical thinkers, as well as producers, consumers, and distributors of technology.
- Quantum information and computing are inherently interdisciplinary subjects, and teaching students how to program can facilitate application of quantum computing techniques.
- Practices should include attention to detail, careful planning and execution of multi-step procedures, facility with basic math, thoughtful data analysis, and clear communication.
- Computational thinking skills and processes (decomposition, pattern recognition, abstraction, and algorithm design) can be taught through discipline-specific projects from computer science, math, science, and the humanities
- Key practices would be algorithm design (sequences of steps and the language used to give instructions), data collection and analysis (deciding when to use quantitative vs. qualitative data, simple graphing)), and abstraction (recognizing patterns).
- Develop a variety of skills with respect to scientific competence, ability to work independently, and interpersonal skills. In addition to skills in the areas of research ethics, scientific skills, and research communication.
- Include use of appropriate tools (including digital tools)
- Integrate research ethics, scientific skills, and research communication in STEM courses at the same time as engaging in data analytics, scientific modeling, and informatics
- Draw from convergence research which acknowledges that the grand challenges cannot be solved by one discipline alone, and is supported by open-source training materials, data sets, and code
- Includes opportunities to conduct experiments, have access to tools and spaces for hands-on and digital modelling and simulations including use of virtual experiments and video recorded experiments.

[111] Notice of Request for Information on STEM Education.

Appendix 2 Federal Cybersecurity Education and Workforce Development Programs

Examples of Federal Cybersecurity Education and Workforce Development Programs and other activities presented in alphabetical order.

CyberCorps®: Scholarship for Service. The Cybersecurity Enhancement Act of 2014, as amended by the National Defense Authorization Acts for 2018 and 2021, and the CHIPS and Science Act of 2022, authorizes the National Science Foundation (NSF), in coordination with the Office of Personnel Management (OPM) and the Department of Homeland Security (DHS), to offer a scholarship program to recruit and train the next generation of cybersecurity professionals to meet the needs of the cybersecurity mission of federal, state, local, and tribal governments. The goals of the CyberCorps® Scholarship for Service (SFS) program are aligned with the U.S. strategy to develop a superior cybersecurity workforce. Program goals are to: (1) increase the number of qualified and diverse cybersecurity candidates for government cybersecurity positions; (2) improve the national capacity for the education of cybersecurity professionals and research and development workforce; (3) hire, monitor, and retain high-quality CyberCorps® graduates in the cybersecurity mission of the federal government; and (4) strengthen partnerships between institutions of higher education and federal, state, local, and tribal governments. While all three agencies work together on all four goals, NSF's strength is in the first two goals; OPM's in goal (3); and DHS in goal (4).

CyberNet Academy. The Department of Education Career and Technical Education (CTE) CyberNet was developed as a starting blueprint that could be adapted to the unique needs of local education ecosystems. The CTE CyberNet developed and refined the design process for implementation in communities with a range of stakeholder needs. With input from subject matter experts, the Department of Education identified three Centers of Academic Excellence Regional Resource Centers uniquely qualified to design, host, and lead the inaugural cohort of CTE CyberNet academies during summer 2020 and the 2020-21 academic year. The Department of Education also oversees the Presidential Cybersecurity Education Award which is presented annually to two educators who demonstrate superior achievement in instilling skills, knowledge, and passion with respect to cybersecurity and cybersecurity-related subjects. The award recognizes demonstrated superior educator accomplishment as well as academic achievement by the educator's students.

CyberForce® Program. This Department of Energy program is focused on inspiring and developing the next generation of cybersecurity professionals to defend and protect our nation's critical infrastructure from cyber threats and attacks. This workforce development program focuses on building a pipeline of cyber professional candidates in operational technology cybersecurity and features hands-on competitions, informational webinars, virtual career fairs, and a workforce portal for participants. The CyberForce Competition® component of the program is a collegiate, team-based competition with a defend/attack energy cyber scenario focused on the hardening nature of cybersecurity for critical infrastructure. Teams defend a simulated virtual infrastructure against Red Team attackers. This competition incorporates life-like constraints and tasks, and continual emerging threats.

Cybersecurity Education and Training Assistance Program (CETAP). Operating for more than a decade and codified in the Fiscal Year 2021 National Defense Authorization Act (NDAA), CETAP is a DHS grant awarded to a non-profit partner to support cybersecurity education in K–12 classrooms through the development of cybersecurity curricula and instructor training.

National Centers of Academic Excellence in Cybersecurity (NCAE-C). Since 1999, NCAE-C has been promoting high-quality cybersecurity education at colleges and universities across the country. In the last five years, NCAE-C academic and student development requirements have shifted to emphasize collaboration between institutions, competency-based education, and development of graduates ready for careers in cybersecurity. Additional funding in the past three years has accelerated program growth and helped the NCAE-C program leverage collaboration with partner institutions to achieve workforce goals in communities across the nation and prepare teachers and faculty to teach cybersecurity. The funding has also allowed NCAE-C to create a curriculum repository, curate the quality of cybersecurity curricula nationwide, create a career pathway from middle school to post-secondary education to the workforce, and begin nine community-based initiatives to develop local cybersecurity education and economic development. Through the NCAE-C program, an established community and network of regional hubs support more than 370 institutions. Recently, the program has also developed the Cybersecurity Education Diversity Initiative, which works to connect minority-serving institutions with mentorship and assistance to advance their educational offerings in cybersecurity. The NCAE-C Program Office is also the executive administrator for DoD's Cyber Scholarship Program which provides support for education at NCAE-C institutions as a recruitment benefit to students who are not currently DoD employees and as a retention incentive to current employees and military members.

National Initiative for Cybersecurity Education (NICE). A federal office that operates in partnership with other government stakeholders, academia, and industry, NICE works to "energize, promote, and coordinate" the cybersecurity education and workforce development community. Through the development of the Workforce Framework for Cybersecurity (NICE Framework), the office has created a shared lexicon to describe cybersecurity work and the knowledge and skills that cybersecurity practitioners should possess. Both because congressional legislation has required its use in federal workplaces and as a natural result of industry uptake, more stakeholders are using the NICE Framework. The NICE program office serves as a hub for cybersecurity education and workforce development by hosting annual conferences, working groups, and communities of interest.

Office of Personnel Management (OPM) Workforce Programs. OPM is tasked with HR functions, OPM has played a key role in federal cyber workforce development. OPM defines the various qualifications, classifications, and requirements that give structure to federal cybersecurity personnel actions, and establishes the rules for various flexibilities that help respond to the high demand for cybersecurity professionals. For example, OPM has established direct-hire authority and pay flexibilities that can be used to alleviate some of the challenges of federal cybersecurity hiring. OPM has also provided pivotal guidance to departments and agencies as they implement the requirements of the Federal Cyber Workforce Assessment Act of 2015, which leverages the NICE Framework to provide a count of federal cybersecurity work roles of critical need. OPM also provides cybersecurity and IT program management competency models, interpretive guidance, and a range of training efforts to improve cyber hiring.

Regional Alliances and Multistakeholder Partnerships Stimulating (RAMPS) Cybersecurity Education, Training, and Workforce Development. Section 9401(f) of the Fiscal Year 2021 NDAA requires NIST to establish RAMPS cybersecurity education, training, and workforce development. These partnerships, previously piloted by NICE, would identify and strive to fill local workforce needs. RAMPS can create a diverse and geographically distributed array of programs, all with the shared goal of bolstering the cybersecurity workforce.

Appendix 3: Data Science Education Learning Frameworks and Practices

While data science education is a relatively new subject in K–12 contexts, it draws upon existing theory in related fields including statistics education, computer science education, and STEM education at-large. Threads of data science education learning frameworks and practices can be found in the Guidelines for Assessment and Instruction in Statistics Education (GAISE II),[112] which was updated to reflect changes in applied statistics and modern data analytics;[113] the K–12 Computer Science Framework, Data and Analysis,[114] and the Next Generation Science Standards, Science and Engineering Practices, Practice 4: Analyzing and Interpreting Data.[115] Each of these learning frameworks provides an example for the inter-disciplinary nature of data science, as well as its potential for integration across existing K–12 subjects.

Researchers are still working to improve theory and practice for teaching the *unique* data science skillsets and knowledge, which distinguish course material from traditional statistics or computer science education models. A recent Technical Working Group hosted by the National Center for Education Research (NCER) highlighted topics including data collection, production, and structures; data processing and storage; data management, curation, and sharing; exploratory data analysis; data security, privacy, and ethics; universal data acumen; data visualization; and communicating about data in public contexts.[116] Additional investment in exploring best teaching practices for these topics and others is necessary. Additionally, pedagogical best-practice for advanced topics in multiple linear regression, predictive analytics, machine-learning, and other "big data" has yet to be deeply researched in K–12 contexts, though some high school programs are already engaging students in these topics and have been for multiple years.

Multiple efforts have created learning frameworks for data science education programs, both in the United States and internationally. In 2019, an international consortium of researchers developed learning frameworks to cover these more unique skills including advanced topics such as machine-learning and recommendation algorithms.[117] Research teams at Stanford University and Brown University have also created learning frameworks for data science programs across grade-levels[118] and multiple school subjects.[119]

NSF-funded research has enabled the creation of multiple high school curricula, software tools, teacher training programs, and after-school enrichment opportunities. One of the first high school courses, Introduction to Data Science (IDS),[120] was developed through an NSF Mobilize grant,[121] and implemented in Los Angeles Unified School District starting in 2015. The IDS program has since scaled

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112 https://www.amstat.org/asa/files/pdfs/GAISE/GAISEIIPreK-12_Full.pdf

113 Schanzer, E., Integrated Data Science for Secondary Schools: Design and Assessment of a Curriculum.

114 K–12 Computer Science Framework. (2016). https://k12cs.org/framework-statements-by-concept/#jump-data-analysis

115 Next Generation Science Standard. (2013). Appendix F: Science and Engineering Practices, https://www.nextgenscience.org/sites/default/files/resource/files/Appendix%20F%20%20Science%20and%20Engineering%20Practices%20in%20the%20NGSS%20-%20FINAL%20060513.pdf

116 National Center for Education Research, *Catalyzing a New Field: Data Science in K-12 Education*

117 International Data Science in Schools Project. (2019). *Curriculum Frameworks for Introductory Data Science*. http://idssp.org/files/IDSSP_Frameworks_1.0.pdf

118 https://www.youcubed.org/resource/data-literacy/

119 Schanzer, E., Integrated Data Science for Secondary Schools: Design and Assessment of a Curriculum.

120 https://www.idsucla.org/

121 https://www.nsf.gov/awardsearch/showAward?AWD_ID=0962919&HistoricalAwards=false

to over nine states and even Australia. NSF funding also contributed to the development of the *Common Online Data Analysis Platform*,[122] a data science instructional software for students starting in middle school.[123]

These early investments catalyzed the creation of multiple programs at all grade-levels since 2015, the majority of which have been articulated as courses or cross-grade learning strands within K–12 mathematics progressions. Additional resources have been or are currently under development for K–12 lessons and units within biology, chemistry, physics, history, economics, sports/physical education, and more.

Grades K–8

- Youcubed K–12 Lesson Plans[124] (middle school modules)
- Youcubed Data Talks[125] (elementary and middle school activities)
- Tableau Data Kids[126] (elementary and middle school activities)
- EDC Streams of Data[127] (forthcoming, elementary activities)

Grades 9–12

- Bootstrap Data Science[128] (1-year high school course, via custom modules)
- CourseKata Statistics & Data Science[129] (1-year high school course)
- TUVA Content Library[130] (lesson plans and activities, all grades)
- UCLA CenterX Introduction to Data Science[131] (1-year high school course) course)
- UC Berkeley Data8[132] (undergraduate introductory course, adopted for high school)
- Youcubed Explorations in Data Science[133] (1-year high school course)
- EDC Data Collection and Analysis[134] (forthcoming, preK activities)

Out-of-School Time

- Young Data Scientists League[135] (YDSL, high school extracurricular)
- TERC Data Clubs[136] (middle school extracurricular)

Promising Classroom Practices

While the field is rapidly expanding, early research and practitioner experience suggests several promising strategies to impart data science education in ways that engage students, imparts rigorous content, and expands student interest in STEM and STEM-adjacent pathways.

Use real-world datasets to engage. A primary opportunity for data science is its immediate relevance to students. Student projects with top music charts, social media trends, sports analytics, or space and

[122] https://codap.concord.org/
[123] https://www.nsf.gov/awardsearch/showAward?AWD_ID=1435470&HistoricalAwards=false
[124] https://www.youcubed.org/data-science-lessons/
[125] https://www.youcubed.org/resource/data-talks/
[126] https://www.tableau.com/data-for-kids
[127] http://oceansofdata.org/projects/streams-data-nurturing-data-literacy-elementary-earth-science
[128] https://www.bootstrapworld.org/materials/data-science/
[129] https://coursekata.org/
[130] https://tuvalabs.com/content
[131] https://www.idsucla.org/
[132] https://data.berkeley.edu/external/data8-adoption
[133] https://hsdatascience.youcubed.org/
[134] http://oceansofdata.org/projects/preschool-data-collection-and-analysis-dca
[135] https://www.youngdatascientists.org/
[136] https://www.terc.edu/dataclubs/

astronomy data can serve as ways to excite students and learn data science in the process (see YDSL sample projects).[137] Mimicking the practice of data analysis in the real-world can promote deeper content understanding and foster better knowledge transfer.[138] Educators should consider promoting dataset selection that will engage students in learning – including through collecting their own data or through explicit training in finding and considering secondary-source data – especially given the modern complexity of the latter. Researchers are developing frameworks to capture the nuanced layers of modern data engagement.[139] Curriculum designers have also identified benefits for non-cleaned or "messy data," and focus on engaging students in the distinct process of deciphering data validity in the context of the modern information era.[140]

Early exposure is critical. Any student on the internet is already engaging with data; many students already have pre-conceived notions of what data is and is not,[141] likely before entering high school. Engaging students in an expanded definition of mathematics early-on may be a productive way to drive later achievement.[142] Middle school in particular is a critical intervention point in a student's academic trajectory, where academic identity is formed, and students decide if they are "math people" or not.[143] Two decades of research on informal statistical inference provide a foundation for integrating key principles in early K–5 learning, including (1) generalization (2) the use of data as evidence for generalization and (3) practice with probabilistic language and reference to levels of certainty.[144] These principles build on existing foundation of measurement and data and expand the typical focus on procedures like calculations of averages or interpretations of graphs.

Relevant technology. Striking a balance for technology up-skilling that empowers learning rather than technology confusion that creates barriers for learning will be critical.[145] Data science often uses computer programming as a means to an end, rather than an end in itself.[146] Referenced curriculum have adopted multiple approaches to tackle this problem, from education-specific data software (Bootstrap, TUVA), to rigorous practice in one professional tool (IDS, Data8), to integrated light-touch programming (CourseKata), to a cannon of accessible software (youcubed). Across tools, early work has shown promise in emphasizing *data moves*, such as filtering, calculating new variables, and changing or merging data structures.[147] Many data professionals will use a variety of tools and programming

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137 https://www.youngdatascientists.org/

138 Fries, L., Son, J., Givvin, K., & Stigler, J. (2020). Practicing Connections: A Framework to Guide Instructional Design for Developing Understanding in Complex Domains. *Educational Psychology Review*, 33:739–762: https://doi.org/10.1007/s10648-020-09561-x

139 Lee, V. R., Wilkerson, M. H., & Lanouette, K. (2021). A Call for a Humanistic Stance Toward K–12 Data Science Education. *Educational Researcher*, *50*(9), 664–672. https://doi.org/10.3102/0013189X211048810

140 LaMar, T., & Boaler, J. (2021). The importance and emergence of K-12 data science. *Phi Delta Kappan*, *103*(1), 49–53. https://doi.org/10.1177/00317217211043627

141 National Center for Education Research. (2022). *Catalyzing a New Field: Data Science in K-12 Education.*

142 Russell, S., & Corwin, R. (1990). *Sorting: Groups and Graphs. Used Numbers. Grades 2-3*. Addison-Wesley Publishing Co, Palo Alto, CA. https://files.eric.ed.gov/fulltext/ED328449.pdf

143 Allen, K., & Schnell, K. (2016). Developing Mathematics Identity. *National Council of Teachers of Mathematics*. 21(7). https://eric.ed.gov/?id=EJ1092791

144 Makar, K., & Rubin, A. (2009). A Framework for Thinking about Informal Statistical Inference. https://iase-web.org/documents/SERJ/SERJ8(1)_Makar_Rubin.pdf

145 Krishnamurthi, S., & Fisler, K. (2019). Programming Paradigms and Beyond. *Cambridge Handbook of Computing Education Research*. https://www.cambridge.org/core/books/abs/cambridge-handbook-of-computing-education-research/programming-paradigms-and-beyond/897D03AD2F26D9680F208BE93EBCF09E

146 International Data Science in Schools Project. (2020). *Curriculum Frameworks for Introductory Data Science*.

147 Erickson, T., Wilkerson, M., Finzer, W., & Reichsman, F. (2019). Data Moves. *Technology Innovations in Statistics Education*, 12(1). https://doi.org/10.5070/T5121038001

languages over the course of their career, especially when switching jobs. The same will likely be true across many future careers. Identifying ways to maximize skills transfer will therefore be critical.

Project-based integration. Data science is inherently an applied discipline, necessitating iterative problem-solving, adaptation, and computational creativity. Integrating project-based learning practices[148] with data science content can foster stronger motivation and task-commitment, problem-solving and higher-level thinking, and help educators meet existing practice standards in mathematics or science.[149] Using datasets as the basis for projects in multiple school subjects (science, social studies, humanities, etc.) can also complement a dedicated course or course sequence.[150] Data science also requires holistic student sensemaking in the process of identifying problems, exploring contexts for problems, and identifying the suitability of available data; more research is needed to define sensemaking in the context of data science.

[148] Condliffe, B., Quint, J., Visher, M., Bangser, M., Drohojowska, S., Saco, L., & Nelson, E. (2017). Project-Based Learning: A Literature Review. MDRC. https://www.mdrc.org/sites/default/files/Project-Based_Learning-LitRev_Final.pdf

[149] Erwin, R. (2015). Data literacy: Real-world learning through problem-solving with data sets. *American Secondary Education*, 18-26.

[150] Vahey, P., Rafana, K., Patton, C., Swan, K., Hooft, M., Kratcoski, A., & Stanford, T. (2012). A cross-disciplinary approach to teaching data literacy and proportionality. *Educational Studies in Mathematics*, 81(2), 179-205. https://www.jstor.org/stable/23254237

Appendix 4: Federal Manufacturing Education and Workforce Development Programs

Manufacturing USA[151] is an interagency effort with 16 institutes sponsored by the Departments of Commerce, Energy, and Defense, aimed at promoting U.S. advanced manufacturing innovation, workforce, and supply chain through public-private partnerships. Each institute aligns education and workforce development efforts in their respective sectors – with a focus on increasing the digital competencies related to current and novel advanced manufacturing technologies.

The NIST Manufacturing Extension Partnership[152] is a national network located in all 50 states and Puerto Rico dedicated to providing a local approach to developing the skills and knowledge to enhance productivity and technological performance of U.S. manufacturing. They are a strong resource for state-level initiatives and networks to promote digital tool and computational literacy development in manufacturing.

The goal of NSF's Future Manufacturing[153] solicitation is to support fundamental research and education of a future workforce to overcome scientific, technological, educational, economic, and social barriers to catalyze new manufacturing capabilities. This initiative couples with NSF's Advanced Manufacturing[154] program to support fundamental research needed to revitalize American manufacturing to grow national prosperity and the workforce, and to reshape our strategic industries. Additionally, NSF's Advanced Technical Education[155] program supports the education of technicians for the high-technology fields that drive our nation's economy by promoting improvement in the education of science and engineering technicians at the undergraduate and secondary institution school levels. These efforts are great avenues for post-secondary education research and initiatives that focus on advancing computational literacy.

In addition, there are several external resources. These include:

- The National Association of Manufacturers Manufacturing Institute[156] is dedicated to bringing Industry 4.0 to manufacturing through educating the workforce of today and tomorrow. They utilize their industry membership to develop initiatives that focus on upskilling and certifications needed to compete for the jobs of the future, with a lens for diversity, equity, and inclusion.
- *ToolingU*[157] is a workforce development platform that provides training to narrow the manufacturing skills gap with a focus on computational tools and learning. They aim to fill the manufacturing pipeline by providing skilled workers, and by upskilling incumbent workers on the new and changing technology needed to compete in a global economy.
- The Society of Manufacturing Engineers[158] is a member organization that accommodates professionals, students, and educators to provide awareness of opportunity, enhance

151 https://www.manufacturingusa.com/institutes
152 https://www.nist.gov/mep/centers
153 https://new.nsf.gov/funding/opportunities/future-manufacturing-fm
154 https://new.nsf.gov/funding/opportunities/advanced-manufacturing-am
155 https://new.nsf.gov/funding/opportunities/advanced-technological-education-ate
156 https://www.themanufacturinginstitute.org/initiatives/
157 https://www.toolingu.com/education
158 https://www.smeef.org/

academic experiences, and directly help students at every level, offering a path to explore, learn and grow through scholarships, student competitions, mentorship, and student summits. They also work with educators to impact the future generation of manufacturing practitioners with free resources that align with computational literacy objectives.

Appendix 5: Nine Key Quantum Information Science Concepts

On behalf of the Interagency Working Group on Workforce, Industry and Infrastructure, under the NSTC Subcommittee on Quantum Information Science (QIS), the National Science Foundation held a workshop[159] that identified key concepts that would provide secondary school students with an understanding of quantum information science that could propel them into quantum-related college pursuits.

- Quantum information science (QIS) exploits quantum principles to transform how information is acquired, encoded, manipulated, and applied. Quantum information science encompasses quantum computing, quantum communication, and quantum sensing, and spurs other advances in science and technology.
- A quantum state is a mathematical representation of a physical system, such as an atom, and provides the basis for processing quantum information.
- Quantum applications are designed to carefully manipulate fragile quantum systems without observation to increase the probability that the final measurement will provide the intended result.
- The quantum bit, or qubit, is the fundamental unit of quantum information, and is encoded in a physical system, such as polarization states of light, energy states of an atom, or spin states of an electron.
- Entanglement, an inseparable relationship between multiple qubits, is a key property of quantum systems necessary for obtaining a quantum advantage in most QIS applications.
- For quantum information applications to be successfully completed, fragile quantum states must be preserved, or kept coherent.
- Quantum computers, which use qubits and quantum operations, will solve certain complex computational problems more efficiently than classical computers.
- Quantum communication uses entanglement or a transmission channel, such as optical fiber, to transfer quantum information between different locations.
- Quantum sensing uses quantum states to detect and measure physical properties with the highest precision allowed by quantum mechanics.

159 https://files.webservices.illinois.edu/9156/keyconceptsforfutureqislearners5-20.pdf

Appendix 6: Literature Review on Building Computational Literacy

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