CONVERGENCE EDUCATION: A GUIDE TO TRANSDISCIPLINARY STEM LEARNING AND TEACHING

A Report by the

INTERAGENCY WORKING GROUP ON CONVERGENCE

FEDERAL COORDINATION IN STEM EDUCATION SUBCOMMITTEE

COMMITTEE ON STEM EDUCATION

of the

NATIONAL SCIENCE AND TECHNOLOGY COUNCIL

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Interagency Working Group on Inclusion in STEM (IWGIS), in response to Section 308 of the 2017 American Innovation and Competitiveness Act and focuses on broadening participation in STEM. A sixth IWG was formed in response to the 2020 Supporting Veterans in STEM Careers Act to improve veteran and military spouse equity and representation in STEM fields and careers.

About the Interagency Working Group on Convergence

Identified as one of four pathways with cross-cutting approaches to achieve the vision and goals of the 2018 Federal STEM Education Strategic Plan, ***engaging students where disciplines converge*** seeks to make STEM more meaningful and inspiring to students by focusing on complex real-world problems and challenges that require initiative and creativity. Under the IWG on Convergence (IWGC), agencies are working to foster educational opportunities that advance innovation and entrepreneurship, where the convergence of ideas at the intersection of different fields gives rise to new technologies, including through competitions, challenges, and educator upskilling opportunities that engage participants in mission-focused areas. The efforts of the IWGC are organized around three central objectives, as outlined in the 2018 Federal STEM Education Strategic Plan: (1) Advance Innovation and Entrepreneurship Education, (2) Make Mathematics a Magnet, and (3) Encourage Transdisciplinary Learning.

About this Document

While much work has been done to promote and advance convergence education over the past decade, a distinct and common framework is beneficial to the concept of convergence education being adopted and universally recognized. Therefore, based on extensive literature review and stakeholder engagement, the IWGC developed a definition and overarching guidance related to convergence education, which are the basis for this report. The intended audience is Federal Agencies and other STEM education stakeholders, with the intended use of this document being to support the understanding and implementation of convergence education. This document is particularly aligned to the IWGC objective to "encourage transdisciplinary learning" because it addresses the key federal action to support research, development, and dissemination on effective transdisciplinary STEM education practices, programs, and policies; and, it ensures Federal activities support the upskilling of educators reflecting transdisciplinary approaches featuring teaching that focuses on local and global community questions. However, it also incorporates connections to the objectives to "advance innovation and entrepreneurship education" and "make mathematics a magnet."

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Abbreviations and Acronyms

CoSTEM	Committee on STEM Education
DHS	Department of Homeland Security
DOC	Department of Commerce
DOD	Department of Defense
DOE	Department of Energy
DOI	Department of the Interior
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
IWG	Interagency Working Group
IWGC	Interagency Working Group on Convergence
NASA	National Aeronautics and Space Administration
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
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

Identified as one of four pathways with cross-cutting approaches to achieve the vision and goals of the 2018 Federal STEM Education Strategic Plan,[2,3,4,5] ***engaging students where disciplines converge*** seeks to make STEM more meaningful and inspiring to students by focusing on real-world problems and challenges that require initiative and creativity. Convergence education is a transdisciplinary approach to teaching, learning, and assessment that focuses on the areas where STEM disciplines converge, such as tackling climate change, pandemic readiness and prevention, emerging technologies, and innovation and entrepreneurship.[6]

As defined by the Interagency Working Group on Convergence (IWGC), **convergence education** is driven by compelling or complex socio-scientific problems or topics, where learners apply knowledge and skills using a blended approach across multiple disciplines (i.e., transdisciplinary) to create and innovate new solutions.

Section I of this document provides a general overview of the research on convergence education and the application of transdisciplinary learning to STEM education. Section II offers a pedagogical framework for convergence education and uses the literature review from Section I to define what is meant by "convergence education"; outlines characteristics, goals, and benefits of convergence education; provides recommended tools and processes for achieving convergence education; outlines a pathway to convergence education through STEM teaching, learning, and assessment, including classroom examples of each; provides a summary of promising and established practices, challenges, and barriers; and then ends with recommendations for stakeholders.

The included resources developed by the IWGC, and presented in this document, are designed to help and encourage Federal agencies and STEM education stakeholders to incorporate convergence education into their work. The intended audience of this report is Federal agencies and other STEM education stakeholders, and while the report is not designed to directly address the educator community, it includes useful tools, language, and examples for agencies and stakeholders to leverage. Convergence education is an approach that best equips students to tackle the world's most pressing challenges and opportunities of the 21st century, which are inherently transdisciplinary. We invite agencies and stakeholders to consider how the pedagogical concept and framework outlined in this document can be used and incorporated into their unique STEM education programs and opportunities.

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[2] https://trumpwhitehouse.archives.gov/wp-content/uploads/2018/12/STEM-Education-Strategic-Plan-2018.pdf
[3] https://trumpwhitehouse.archives.gov/wp-content/uploads/2019/10/Progress-Report-on-the-Federal-Implementation-of-the-STEM-Education-Strategic-Plan.pdf
[4] https://trumpwhitehouse.archives.gov/wp-content/uploads/2017/12/Progress-Report-Federal-Implementation-STEM-Education-Strategic-Plan-Dec-2020.pdf
[5] https://www.whitehouse.gov/wp-content/uploads/2022/01/2021-CoSTEM-Progress-Report-OSTP.pdf
[6] As outlined in the Federal STEM Education Strategic Plan, the efforts of the IWG-C are organized around three central objectives: (1) Advance Innovation and Entrepreneurship Education, (2) Make Mathematics a Magnet, and (3) Encourage Transdisciplinary Learning. The resources and content presented in this document are particularly aligned with the third objective, to "encourage transdisciplinary learning." However, given the nature of convergence education, as defined in this document, learning is driven by a deep integration across multiple disciplines. Efforts towards these three objectives are inherently intermingled, and additional updates and progress towards all objectives may be found in the CoSTEM annual progress reports on the implementation of the Federal STEM Education Strategic Plan.[3,4,5]

Understanding the path forward to successful convergence education required engagement, input, and coordination from both key external stakeholders and federal agencies. Insights from these groups clarified the current state of convergence education, drivers and barriers to implementation of convergence education, and the potential future state of convergence education.

Section I: General Overview of Research on Convergence Education

In 2016, the National Science Foundation (NSF) identified convergence research as one of 10 "Big Ideas for Future NSF Investments." NSF defined **convergence research** as:

> "*a means of solving vexing research problems, in particular, complex problems focusing on societal needs. It entails integrating knowledge, methods, and expertise from different disciplines and forming novel frameworks to catalyze scientific discovery and innovation. Convergence research is related to other forms of research that span disciplines - transdisciplinarity, interdisciplinarity, and multidisciplinarity. It is the closest to transdisciplinary research which was historically viewed as the pinnacle of evolutionary integration across disciplines.*"[7]

In 2019, NSF, the Organization for Economic Cooperation and Development (OECD), the US National Academies of Sciences, Engineering, and Medicine (NASEM), and the University of Southern California sponsored a workshop, with global participation, to explore actions that would facilitate convergence in education.[8] This workshop addressed the outlook and needs for applying convergence across the stages of preK-20 education.

In 2020, the Federal Coordination in STEM Education (FC-STEM) Interagency Working Group (IWG) on Convergence conducted a literature review on convergence education[9] (Appendix 1). In translating this concept[10] to STEM education, the terms *transdisciplinary* or *integrated STEM* are often used analogously. This literature review was done to establish a basis of reference for further understanding *convergence education* and its relationship to *transdisciplinary learning* or *integrated STEM* education[11]. To that end, the IWGC defined convergence education as driven by compelling or complex socio-scientific problems or topics, where learners apply knowledge and skills using a blended approach across multiple disciplines (i.e., transdisciplinary) to create and innovate new solutions. Socio-scientific problems or topics are real-world, socially-relevant, informed by science, and often include an ethical component, with examples such as climate change, energy security, biotechnology, infectious disease, and water scarcity.

While much work has been done to teach students about complex real-world problems and topics[12,13], it would be beneficial to have a distinct and common framework for convergence education that is universally recognized. Most of the literature to date, for example, agrees that transdisciplinary learning produces critical thinkers and engaged learners, and it instills more workforce readiness skills in

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[7] National Science Foundation. (ND). Convergence Research at NSF. Available: https://www.nsf.gov/od/oia/convergence/index.jsp

[8] Herr, D.J.C., Akbar, B., Brummet, J. *et al.* (2019). Convergence education—an international perspective. *Journal of Nanoparticle Research, (21)*229. Available: https://doi.org/10.1007/s11051-019-4638-7

[9] https://ssec.si.edu/transdisciplinary-learning

[10] Bainbridge, W. S. (2004). Early convergence research and education supported by the National Science Foundation. In M. C. Roco & C. D. Montemagno (Eds.), Coevolution of Human Potential and Converging Technologies (Vol. 1013, pp. 234–258). New York Acad Sciences. https://doi.org/10.1196/annals.1305.017

[11] admin. (2016, May 23). Transdisciplinary approach—UNESCO International Bureau of Education Definition [Text]. International Bureau of Education. http://www.ibe.unesco.org/en/glossary-curriculum-terminology/t/transdisciplinary-approach

[12] Cook, K. L., & Bush, S. B. (2018). Design Thinking in Integrated STEAM Learning: Surveying the Landscape and Exploring Exemplars in Elementary Grades. *School Science and Mathematics, 118*, 93–103. https://doi.org/10.1111/ssm.12268

[13] Gibson, H. (2021). *From Ideas to Action: Transforming Learning to Inspire Action on Critical Global Issues.* Open Monographs. Washington, DC: Smithsonian Institution Scholarly Press. Book. https://doi.org/10.5479/si.15173715.v1.

students than traditional education models[14,15]. In particular, it fosters innovation and the ability to solve complex societal issues[16].

However, it has been difficult to assess or measure how effective transdisciplinary learning has been in the classroom due to the comprehensive nature of the disciplines which it embodies,[17] and the current structure of discipline specific standards and assessments in state and local education systems. For example, advanced mathematics is not often incorporated into the structure of transdisciplinary STEM learning and better efforts are needed to integrate challenging mathematical practices and standards into the science content areas within a larger framework of convergence education.[18] The literature tends to indicate that a common framework is needed and should be adopted before an effective assessment methodology can be developed and implemented in a learning environment.[19]

Research Literature on Convergence Education

Convergence education must first be driven by a specific and compelling problem. This type of learning is inspired by the need to address a specific challenge or natural phenomenon.[20] It is driven by the need to enhance society by examining problems that can arise from deep scientific questions or pressing societal needs[21]. Convergence education must also have a deep integration across multiple disciplines.[22] It recognizes that these problems cannot be solved by looking at them through a single lens or a particular mindset. Instead, experts from different disciplines must work together and blend their knowledge, theories, expertise, methods, data, and research to create coherence and comprehensive solutions. Convergence needs to be modeled at every level of education and research and should be incorporated in preK-20 classrooms.

There are varying levels of integration leading up to convergence education: multidisciplinary, interdisciplinary, and transdisciplinary (Table 1). Convergence education strives for transdisciplinary approaches to reach the goal of complete integration of all skillsets, disciplines, and knowledge into a learning model that allows students to tackle the world's most challenging problems. The learning

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[14] https://ssec.si.edu/transdisciplinary-learning

[15] O'Mahony, T. K., Vye, N. J., Bransford, J. D., Sanders, E. A., Stevens, R., Stephens, R. D., Richey, M. C., Lin, K. Y., & Soleiman, M. K. (2012). A comparison of lecture-based and challenge-based learning in a workplace setting: Course designs, patterns of interactivity, and learning outcomes. *Journal of the Learning Sciences, 21*(1), 182–206. https://doi.org/10.1080/10508406.2011.611775

[16] Barnes-Johnson, J., & Johnson, J. M. (2018). STEM21: Equity in Teaching and Learning to Meet Global Challenges of Standards, Engagement and Transformation. Social Justice across Contexts in Education. In Peter Lang Publishing Group. Peter Lang Publishing Group.

[17] Walker, A., and Leary, H. (2009). A problem based learning meta analysis: differences across problem types, implementation types, disciplines, and assessment levels. *Interdiscip. J. Probl. Based Learn.* 3, 12–43. doi: 10.7771/1541-5015.1061

[18] Walker, W. S. (2017). Integrated STEm or Integrated STEM? *School Science and Mathematics, 117*(6), 225–227. https://doi.org/10.1111/ssm.12234

[19] Al Quraan, E. J., & Forawi, S. A. (2019). Critical Analysis of International STEM Education Policy Themes. Jo*urnal of Education and Human Development, 8(*2), 82–98.

[20] Honey, M., Pearson, G., & Schweingruber, H. (2014). *STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research.* Washington, DC: National Academies Press.

[21] 2020 EDUCAUSE Horizon Report | Teaching and Learning Edition. (n.d.). Retrieved December 22, 2020, from https://library.educause.edu/resources/2020/3/2020-educause-horizon-report-teaching-and-learning-edition

[22] National Research Council (2014). Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond. Washington, DC: National Academies Press. https://doi.org/10.17226/18722.

model shown in Table 1 (Section II, page 12-13) demonstrates the increasing "levels of integration" that can occur in a STEM classroom.[23]

Based on this literature review, convergence education should include the following elements for it to be successful.[24] First, the individual subject content areas should be taught thoroughly and with rigor, and standards for the individual content areas should be met (i.e., convergence education requires a foundation in STEM content areas and transdisciplinary learning is not a replacement for discipline-specific teaching & learning)[25]. Research strongly suggests that a correlation exists between a successful development of the disciplinary or domain-specific foundations and the ability to make connections between those disciplines[26]. If the building blocks are not present, transdisciplinary learning cannot occur due to insufficient foundational elements upon which to build. Second, convergence education should be intentional with a clear and explicit plan. Convergence education requires disciplinary, multidisciplinary, interdisciplinary, and transdisciplinary learning (as defined in Section II),[27] which must be proactively designed to combine the practices and create learning experiences that are intentionally and methodically designed. True convergence education occurs under strategic and measured circumstances.

Goals for Engaging Learners where Disciplines Converge

The goals of convergence, as outlined by the 2018 Federal STEM Education Strategic Plan, include: a dedication to STEM literacy and 21st century competencies; preparation to enter the workforce in STEM-related fields; and an enhanced engagement across all disciplines.[28] Above all, the goals are: to develop learners that have the ability to make connections across disciplines, to apply what they are learning to situations found outside of the STEM classroom, and to ensure they are equipped with the requisite knowledge and skill sets required to solve the world's most pressing scientific and societal issues. For teachers, the goals tend to be focused on increasing content knowledge from individual disciplines while also evolving pedagogical skills to better meet the demands of a transdisciplinary learning experience.

Currently, researchers measure success in attaining convergence education goals by observing learners' advancement in 21st century competencies; STEM course enrollment; graduation rates; indicators of persistence, STEM interest, and employment; and the ability for students to make connections between STEM disciplines. These goals and outcomes can help researchers determine a framework that can promote a ***pathway towards convergence education***.

To address these goals and outcomes, this report proposes: key elements of convergence education, what convergence education is and what it is not, goals for students, goals for teachers, recommendations for stakeholders, and a compilation of best practices. The goals of this report are to: (1) monitor evolving practices, approaches, and outcomes of transdisciplinary learning in education; (2) report research in best practices that provide evidence of successful convergence work that will support a pathway to convergence; (3) draw from research evidence-based examples of promising

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[23] Vasquez, J. A., Sneider, C., & Comer, M. (2013). *STEM Lesson Essentials.* Heinemann Educational Books.

[24] Honey, M., Pearson, G., & Schweingruber, H. (2014). *STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research.* Washington, DC: National Academies Press.

[25] Vasquez, J. A., Sneider, C., & Comer, M. (2013). *STEM Lesson Essentials.* Heinemann Educational Books.

[26] The National Academies of Sciences, Engineering, and Medicine. (2014, March 6). STEM Integration in K-12 Education. https://www.youtube.com/watch?v=AlPJ48simtE

[27] Vasquez, J. A., Sneider, C., & Comer, M. (2013). *STEM Lesson Essentials.* Heinemann Educational Books.

[28] https://trumpwhitehouse.archives.gov/wp-content/uploads/2018/12/STEM-Education-Strategic-Plan-2018.pdf

practices; (4) develop and adopt a framework/definition of transdisciplinary learning, teaching, and assessment that can be disseminated to stakeholders in the education ecosystem including government entities, educators, and Tribal communities; and (5) use the research and framework to track the efficacy of federal efforts in transdisciplinary learning.

To achieve these goals and outcomes, there is a great need for collaboration between various stakeholders across the education ecosystem. Educators, administrators, researchers, Federal Agencies, and other governmental entities must come together to collaborate. To achieve a pathway to convergence education the stakeholders must create a coherent framework and definition, encourage investments or scale-up of proven and effective approaches to convergence education, and support the development of initiatives to build an awareness and recognition of the importance of transdisciplinary learning[29]. Together, these efforts help develop students who are ready to use their skills to tackle the most pressing issues of today and the future by advancing innovation and entrepreneurship. These stakeholders must work together to create a culture that supports and promotes teaching pathways to convergence education. The culture can be developed through communities of practice that enable educators and community members to discuss complex scientific and societal challenges, share best practices[30], and innovate solutions in an emergent environment of teaching and learning.

[29] National Research Council 2014. Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond. Washington, DC: The National Academies Press. https://doi.org/10.17226/18722

[30] Herr, D.J.C., Akbar, B., Brummet, J. *et al.* (2019). Convergence education—an international perspective. *Journal of Nanoparticle Research, (21)*229. Available: https://doi.org/10.1007/s11051-019-4638-7

Section II: Framework for Convergence Education

What is Convergence Education?

CONVERGENCE EDUCATION

as defined by the Interagency Working Group on Convergence

Convergence education is driven by compelling or complex socio-scientific problems or topics, where learners apply knowledge and skills using a blended approach across multiple disciplines (i.e. transdisciplinary) to create and innovate new solutions.

Primary Characteristics of Convergence Education

- **Driven by a specific and compelling problem.** Inspired by the need to address a specific challenge or opportunity, whether it arises from complex scientific questions or important societal needs.
- **Incorporates significant integration across disciplines.** As experts from different disciplines pursue common research challenges, their knowledge, theories, methods, data, research communities, and languages become increasingly intermingled and integrated. New frameworks, paradigms, or even disciplines can form across multiple communities.

Convergence education should always be

- **Strategic and measured**; emphasizing quality over quantity
- **Intentional and explicit**; the movement from disciplinary to effective transdisciplinary teaching and learning doesn't just happen
- **Integral, not a replacement**; strong foundational disciplines are still essential and remain strong building blocks

Convergence as a term in education

Convergence as a term was initially coined by the National Science Foundation (NSF) in reference to research that may solve complex problems focusing on societal needs[31]. Convergence research entails integrating knowledge, methods, and expertise from multiple disciplines and forming novel frameworks to catalyze scientific discovery and innovation. In translating this concept to the educational space, the terms *transdisciplinary* or *integrated* are often used analogously, and are likely to be more familiar terms for educators.

Achieving Convergence Education

Increasing Levels of Integration

Convergence education reflects increasing levels of integration across disciplines (as defined below), with the goal state of achieving transdisciplinary teaching, learning, and assessment, along the pathway to convergence. Importantly, the expectation is not that transdisciplinarity is the only or optimal approach; rather, transdisciplinarity may be used in concert with all levels of integration (disciplinarity, multidisciplinarity, and interdisciplinarity); each approach has value and there is a need and role for each. Convergence education cannot be successfully implemented and achieved without

[31] https://www.nsf.gov/od/oia/convergence/index.jsp

the incorporation of all levels of integration, including the focus on a single discipline (disciplinarity). Moreover, the boundaries between these levels of integration are not precisely constrained or defined, affording educators with the requisite flexibility of integration to achieve desired outcomes in convergence education.

- **Disciplinary**: Concepts and skills are approached separately, allowing students to engage and be assessed on a singular discipline, with minimal integration.
- **Multidisciplinary**: A common theme or approach is used to allow students to connect concepts and skills learned separately in each discipline. Multiple disciplines are incorporated but they are not *integrated.*
- **Interdisciplinary**: Students learn concepts and skills from two or more disciplines that are tightly linked so as to deepen knowledge and skills. Educators and learners collaborate to identify a concept involving multiple disciplines in an integrated way that makes the concept authentic and real-world.
- **Transdisciplinary**: Learners identify complex problems and work together to create a shared conceptual framework and draw together theories, concepts, and practices that transcend individual disciplinary boundaries. Focus is on broad, real-world constructs drawn from an increasingly interconnected world, societal relevance, and student interest. Transdisciplinary (including applied interdisciplinary approaches) is distinct from multi- or inter-disciplinary in that subjects are *blended* in a *transformative* manner that provides important gateways for student-centric, student-defined problems or topics that lead to authentic and meaningful learning experiences and student-driven innovations.

Pathway to Convergence Education through STEM Teaching, Learning, and Assessment

A pathway to convergence education in STEM is not feasible without disciplinary STEM foundations and complementary integration approaches. Table 1 outlines specific elements of STEM learning, teaching, and assessment within each level of integration described above.

Table 1: Elements of STEM learning, teaching, and assessment at progressive levels of integration.

	DISCIPLINARY	MULTI-DISCIPLINARY	INTER-DISCIPLINARY	TRANS-DISCIPLINARY
Learning	Students directed by teacher to focus on a single discipline or topic within a content area.	Students directed by teacher to focus on more than one discipline in a unit of study, but the disciplines are not connected as part of the learning experience for the student.	Students focus on more than one discipline in a unit of study and the disciplines are connected to each other but don't have to be fully integrated.	Students focus on broad real-world constructs drawn from our increasingly interconnected world for their relevance and student interest; integrates values, ethics, world views, and student action.
Teaching	Teacher identifies an isolated science, technology, engineering, or math concept (fact, idea, or	Teacher identifies a STEM concept involving multiple STEM disciplines addressed independently on	Students and teachers collaborate to identify a STEM concept involving multiple STEM disciplines (and even other disciplines such as art, social	Teachers work together with those of other disciplines to support students to identify a real-world problem and work together to create a shared conceptual

	practice) and does not approach it in an integrated way.	different aspects of the same concept.	studies, etc.), in an *integrated* way that makes the concept authentic and real-world.	framework and draw together theories, concepts, and practices that transcend individual disciplinary boundaries.
	DISCIPLINARY	**MULTI-DISCIPLINARY**	**INTER-DISCIPLINARY**	**TRANS-DISCIPLINARY**
Assessment	Assessment items address only a singular discipline.	Assessment items address multiple disciplines related to the STEM concept but they are not integrated.	Assessment item is problem or phenomenon based and integrates multiple STEM disciplines and other disciplines.	Assessment item is scenario-based, measuring content knowledge along with creative and critical thinking frameworks, and focused on 21st century learning.
Example	Students examine the properties of soil. Assessment: define soil.	Students examine the properties of soil in one lesson, then they calculate the porosity of soil in another. Assessment; one item assesses science, another math, etc.	Students study the porosity of soil, assess its impact on erosion, and engineer a solution to a soil erosion problem. Assessment: students present their engineered design proposal to solve defined problem.	Students identify an erosion issue in the school community (e.g., drainage related to local construction and propose solutions while exploring related issues such as infectious disease, biohazards, and community relations. Assessment: rubric includes identifying issue and scientific evidence, knowledge, and skills learned.

Goals and Outcomes

We have identified key potential goals and outcomes achieved through convergence education for both learners and educators, which include:

For educators:
- Increased STEM content knowledge in various disciplines
- Increased pedagogical knowledge in innovation and design methodologies

For learners:
- STEM learning and achievement
- 21st century competencies[32], workforce readiness, innovation, and entrepreneurship
- Increased STEM course-taking, educational persistence, and graduation rates
- Gaining STEM interest and career aspirations
- Development of STEM identity
- Ability to make connections among STEM disciplines

[32] https://www.nationalacademies.org/our-work/defining-deeper-learning-and-21st-century-skills

- STEM-related employment, particularly in innately transdisciplinary disciplines, such as Artificial Intelligence and Climate Mitigation

Challenges, Barriers, and Misconceptions

There are specific challenges and barriers that must be considered and addressed to successfully implement convergence education at a large scale. Importantly, failure to consider and address these issues may impede the goals and outcomes successful convergence education can offer. Some of these include:

- No central operational definition or terminology for “convergence” in education and incomplete awareness among educators
- Need for alignment in implementation across grade bands
- Student assessments, standards, and curricula fluctuate frequently and are often discipline specific
- All students may not have similar aptitude or inclination towards certain problems, however, the convergence approach is flexible and offers students voice and choice
- Educators require time to learn and incorporate convergence and require buy-in from peers, administrators, districts, and states
- May need further investigation of the impacts of convergence education on existing gaps in the representation of specific groups in STEM fields (e.g., populations historically underserved and underrepresented in STEM) and, if warranted, the development of potential mitigation strategies

Many of today's challenges and barriers to convergence education are rooted in a shift in education policy. While earlier education policies focused on capacity-building inputs such as developing aid programs and improving access and resources, later education policy ‘reforms’ focused on quantitative measurements of technical outputs, for example through standardized testing. This latter approach focuses on quantities and techniques, rather than curriculum, pedagogy and mindsets (all qualities intrinsic to convergence education). This more recent focus on outputs propels an accountability-based learning environment that is disciplinary and siloed within STEM. This can undermine efforts to develop educational experiences that encourage students to pose meaningful questions and solve challenging complex socio-scientific problems whose answers and solutions invariably cross traditional disciplinary boundary lines in today’s learning environments. However, as noted in the recommendations in a recent NASEM report, there is a need to balance advocacy for STEM broadly with attention to the importance of high-quality learning experiences in science (physics, biology, chemistry, etc.) as well as in each of the other STEM disciplines[33].

Promising and Established Practices

To implement and facilitate convergence education, there are a number of educational practices that may be leveraged which are provided below. Implementing these approaches does not directly equate to convergence education, however these can be promising practices that enable and support the pathway to convergence education. It is important to acknowledge that many of these approaches have been in use by specific research and education communities, for decades in some cases, and therefore certain communities are currently operating with familiarity with practices that can promote

[33] National Academies of Sciences, Engineering, and Medicine 2021. Call to Action for Science Education: Building Opportunity for the Future. Washington, DC: The National Academies Press. https://doi.org/10.17226/26152.

convergence education. For example, Career and Technical Education (CTE) educators and administrators have been leveraging applied interdisciplinary approaches with great success in secondary and postsecondary programs[34]. Similarly, Invention Education[35] has demonstrated increased student engagement in STEM while contributing to the development of characteristics, skills, and mindsets needed for student pathways to innovation and entrepreneurship. These examples from the field represent near-term opportunities to amplify practices that facilitate the path to convergence education, specifically from communities and practitioners with experience and success in those practices.

- **Academic teaming**: instructional process where students collaborate, peer coach and peer teach.[36]
- **Applied Learning**: students learn by engaging in direct application of skills, theories and models.[37]
- **Career and Technical Education**: refers to courses and programs designed to prepare students for careers in current or emerging professions. At the high school level, CTE provides students with opportunities to explore a career theme of interest while learning a set of technical and employability skills that integrate into or complement their academic studies.[38]
- **Engineering Design**: a highly iterative design and decision-making process through which learners refine and troubleshoot the creation of products, processes, and solutions, often referred to as designing under constraint.[39]
- **Inquiry-Based Learning**: engages students by making real-world connections through exploration and high-level questioning; encourages students to engage in problem-solving and experiential learning.[40]
- **Invention Education**: promotes the unique ways that inventors identify problems and seek creative solutions.[41]
- **Phenomenon-Based Learning**: anchoring learning in explaining phenomena, where students may design solutions and build ideas in the context of application and real-world contexts.[42]
- **Place-Based Learning:** immerses students in local heritage, cultures, landscapes, opportunities and experiences, using these as a foundation for the study of subjects across the curriculum and emphasizes learning through participation in service projects for the local community.[43]
- **Problem-Based Learning**: instructional methods are centered on solving complex real-world problems as a vehicle to promote student learning of concepts and principals.[44]

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[34] Learning Policy Institute & Turnaround for Children. (2021). Design principles for schools: Putting the science of learning and development into action.
[35] Flynn, Leslie, Skukauskaite, et.al. (2019) Researching Invention Education, A White Paper, https://inventioneducation.org/wp-content/uploads/LMIT-ResearchingInventEdu-WhitePaper-2.21.2020.pdf
[36] Toth, M. and Sousa, D. (2019). The Power of Student Teams. Learning Sciences International.
[37] https://appliedlearning.buffalostate.edu/types-applied-learning-0
[38] https://www2.ed.gov/datastory/cte/index.html#WHATISCTE
[39] https://www.teachengineering.org/populartopics/designprocess
[40] Bell, R., Banchi, H. (2008). The Many Levels of Inquiry. Science & Children, 46(2), 26-29.
[41] https://inventioneducation.org/invention-education/
[42] https://www.nextgenscience.org/resources/phenomena
[43] https://stemtlnet.org/resources/how-place-based-science-education-strategies-can-support-equity-students-teachers-and
[44] https://citl.illinois.edu/citl-101/teaching-learning/resources/teaching-strategies/problem-based-learning-(pbl)

- **Project-Based Learning**: students learn by actively engaging in real-world and personally meaningful projects[45].
- **Scientific Modeling:** using a representation of a phenomena to reason and test ideas[46].
- **Work-based Learning Experiences**: an instructional strategy that enhances learning by connecting it to the workplace, including the application of academic, technical, and employability skills.[47]

Additional Examples

The below provide additional analogies and examples for convergence education as understood through the lens of increasing integration.
As outlined in Figure 1, understanding levels of integration can be conceptualized through a simple analogy using ice cream:

- *Disciplinary* is represented by individual cones, each containing only one flavor, with no overlap.
- *Multidisciplinary* is represented by a single cone containing multiple flavors; while there are multiple flavors, they remain separate.
- *Interdisciplinary* is represented by an ice cream sundae, where multiple flavors are combined but still recognizable.
- *Transdisciplinary* is represented by a milkshake, where the component elements (ice cream) are *blended* to *create something new*, and where those starting elements can no longer be separated.

[45] https://www.pblworks.org/what-is-pbl
[46] Kenyon, L., Schwarz, C., & Hug, B. (2008). The benefits of scientific modeling. Science and Children, 46(2), 40.
[47] https://cte.ed.gov/wbltoolkit/

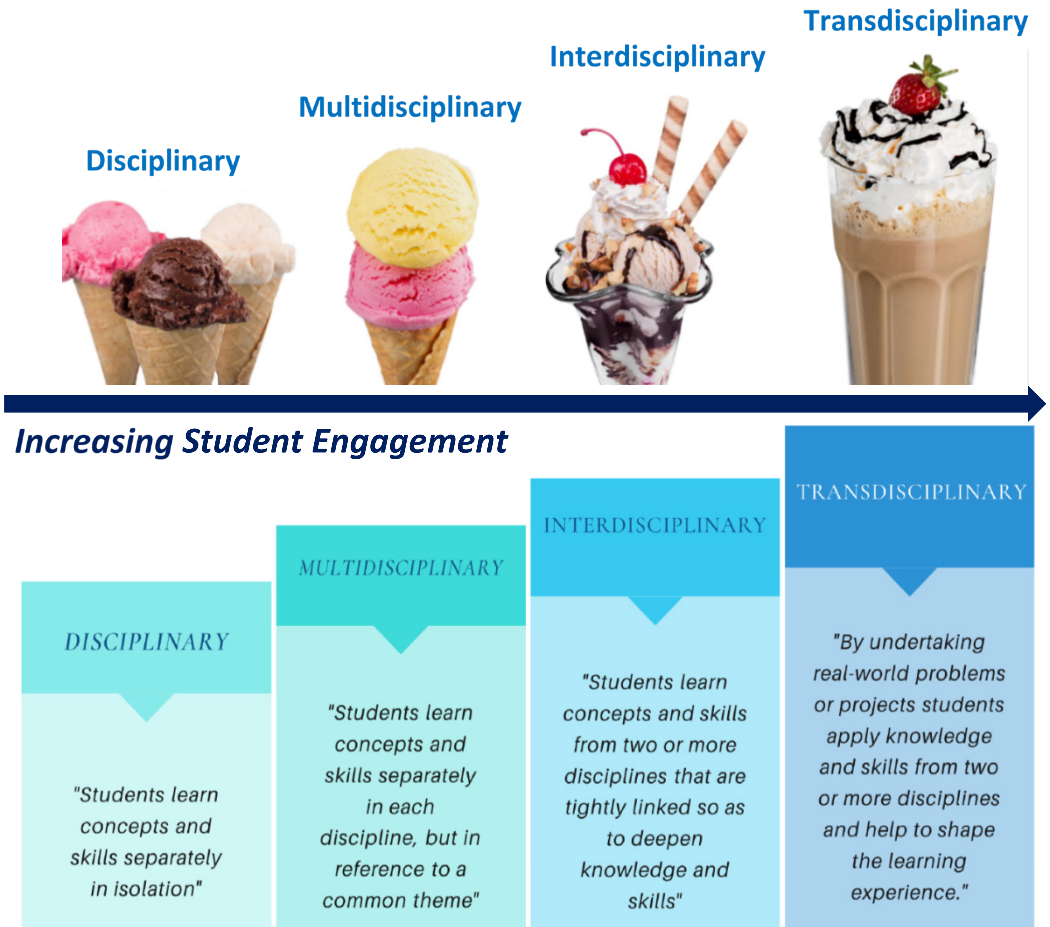

Figure 1. Increasing Levels of Integration. Upper panel (source: IWG-C): Analogy for conceptualizing levels of integration. Lower panel: Vasquez, J.A., Sneider, C., & Comer, M. (2013). STEM lesson essentials, Heinemann Educational Books.

Convergence education is also an opportunity to prepare students for solving complex global challenges and real-world problems. Examples of this include the 15 Global Challenges[48], the United Nations Sustainable Development Goals[49], the NSF Big Ideas[50], and the NASEM Grand Challenges and Opportunities in Environmental Engineering[51], among others.

To further understand how educators in a classroom setting may move from disciplinary to transdisciplinary teaching, learning, and assessment, the following examples are provided to showcase levels of integration around specific topics. Educators may move fluidly across these levels of integration during a learning unit or lesson, which allows for students to develop the critical content knowledge and skills to engage in transdisciplinary learning.

[48] https://www.millennium-project.org/projects/challenges/
[49] https://sdgs.un.org/goals
[50] https://www.nsf.gov/news/special_reports/big_ideas/convergent.jsp
[51] https://www.nationalacademies.org/our-work/grand-challenges-and-opportunities-in-environmental-engineering-for-the-twenty-first-century

Tables 2-4 focus on specific examples and provide sample templates for how educators might move from disciplinary to transdisciplinary on any number of complex topics. As noted, the transdisciplinary level presents the opportunity to engage and develop learners' 21st Century Learning Skills, including critical thinking, collaboration, creativity, and communication.

Table 2: Example of Ocean Acidification lesson(s) with varying levels of integration.

DISCIPLINARY	MULTI-DISCIPLINARY	INTER-DISCIPLINARY	TRANS-DISCIPLINARY
• Define ocean acidification (OA) and list its causes. • Understand acid-base (A/B) chemistry (Arrhenius definition), pH and the pH scale, weak vs strong A/B, use of appropriate indicators, A/B as electrolytes, neutralization, and titration. • Create study cards that summarize the different impacts of changing pH on living things. • Review the chemical reaction mechanism producing carbonic acid • Determine the composition and production of ocean water. • <u>Assessment:</u> Quiz	• **Math**: students learn about logarithmic scales in reference to pH. • **English**: students read the graphic novel Tales of the Modern Mariner by Nick Hayes. • **History**: students research mass extinction events in the geological past caused by OA. • **Engineering/ Tech**: students engineer a rain collection device to use probes to test pH of rainwater. • <u>Assessment:</u> Quiz + participation in activities	• Students work in teams to explore the disintegration of chalk in water, salt water, and vinegar. • Teams research the composition of chalk/ocean water and tie into shelled organisms. • Students brainstorm ways to reverse the acidification process. • Teacher or student groups invite a guest speaker – real or virtual – from NOAA. • <u>Assessment:</u> Data interpretation summary report/pamphlet	• Students identify a real-world problem to solve in the context of a scenario. E.g., How can changes in the environment impact living things? What is causing the shells of shellfish or the coral reefs to thin? How can we slow down or reverse this process? (**Critical thinking**) • Working in teams, students research and choose a shelled organism that is impacted by OA. Teams engineer an ocean system, measure and vary the pH, and observe shell changes over time as they manipulate variables. (**Collaboration**) • Teams attempt to remediate the increasing acidification and design solutions, test and retest, collect and analyze data to determine effectiveness. (**Creativity**) • Teams share their oral and written solution by presenting to the class/community at a science fair. (**Communication**) • <u>Assessment</u>: Tiered rubric + 3 minute video presentation

Table 3: Example of Bird Migration lesson(s) with varying levels of integration.

DISCIPLINARY	MULTI-DISCIPLINARY	INTER-DISCIPLINARY	TRANS-DISCIPLINARY
• Identify the species of birds that migrate through your region yearly.	• **Math**: Students count bird sightings for a specific time period and class performs descriptive statistics.	• Students explore the significance and/or possible use of the bird species in other cultures. • Students brainstorm ways to better count	• Students identify a real-world problem to solve in the context of a scenario. E.g. when geese migrate through their community, they leave their droppings in green spaces,

DISCIPLINARY	MULTI-DISCIPLINARY	INTER-DISCIPLINARY	TRANS-DISCIPLINARY
• Introduce scientific vocabulary. • Create study cards that summarize the identifying characteristics of the species. • Identify their bird song or call. • Identify birds' preferred food source. • Class creates a bird food web. • <u>Assessment:</u> Quiz	• **Biology**: Students study migratory maps and patterns using eBird.org data • **History**: Students use historical imagery option in Google Earth to discern changes in green space availability of their community over time. • **Earth Science**: Students collect weather data over time. • <u>Assessment:</u> Quiz + participation in activities	(estimate) the migratory birds. • Students identify problems that arise when birds migrate through a community (i.e. bird droppings). • Teacher or student groups invite a guest speaker – real or virtual – from Audubon Society or local bird-watching group. • Use online data to track changes in population and discuss correlation to climate change. • <u>Assessment</u>: Summary report or presentation	especially the schools' athletic fields. (**Critical thinking**) • Students work in teams to gather data to determine how big a problem this is, and to engineer methods to address it building off prior tasks. (**Collaboration**) • Students design their solution, test and retest, collect and analyze data to determine effectiveness. (**Creativity**) • Teams share their solutions using written and oral presentations of findings to the class, community, or science fair. • <u>Assessment</u>: Tiered rubric + 3-minute video presentation

<u>Table 4:</u> Example of Disabilities and Assistive Technologies lesson(s) with varying levels of integration.

DISCIPLINARY	MULTI-DISCIPLINARY	INTER-DISCIPLINARY	TRANS-DISCIPLINARY
• Define disability. • Identify different types of disabilities. • Label a diagram of the human nervous system. • Create study cards that summarize the characteristics of people with disabilities • Write a paragraph on technologies that help people with disabilities • <u>Assessment:</u> Quiz	• **Math**: Students collect data and graph the number of people with differing abilities in U.S. • **Biology**: Students study the physiological characteristics of people with disabilities. • **History**: Students study the history of the Americans with Disabilities Act (ADA). • **Physics:** Students study forces and motions. • <u>Assessment:</u> Quiz + participation in activities	• Students explore the challenges faced by people with differing abilities. • Students brainstorm ways that other inventors have developed assistive technologies. • Students learn about assistive technology inventions. • Teacher or student groups invite a guest speaker to talk about inventing for people with differing abilities. • Students analyze and display data about technologies that are available for people with disabilities. • <u>Assessment</u>: Summary report, poster, presentation on topic	• Students identify a real-world problem to solve in the context of a scenario. E.g., How can technology help people with differing abilities? What does one need to understand about the needs of those with differing abilities? What assistive technology can be developed to improve their lives? (**Critical Thinking)** • Students work in teams to collect data and talk to people with differing abilities to learn how to address the needs of those with differing abilities. (**Collaboration & Problem Identification**) • Students apply engineering design principles to identify and develop creative inventions. Students use patents for inspiration and learn from other inventions to develop new ones. (**Creativity, Design**) • Teams share or "pitch" their inventive solutions using written and oral presentations of findings to the class, community, investors. (**Communication**) • <u>Assessment</u>: Tiered rubric + 3-minute student video pitch

Recommendations for Stakeholders

In review of the literature, several recommendations for accomplishing and advancing towards convergence education have been proposed[52,53]. Consensus is that all stakeholders should collaborate to build awareness of the role of convergence in advancing science and technology and stimulating innovation for the benefit of society. Moreover, the Interagency Working Group on Convergence recognizes that coordinated efforts and support from both external stakeholders and the federal community are necessary for success. The below recommendations are provided by various Federal Agencies and reflect the collective efforts and work of the IWG Convergence.

- **Education Experts, Foundations, and Funding Organizations** should identify key problems with solutions requiring convergence approaches.
- **Federal Agencies** should support and/or fund efforts to: (1) expand and promote convergence education in practice, including funds to support educator professional development and (2) investigate & identify effective best practices, pedagogy, and metrics of convergence education. This includes the development and/or promotion of key tools required for convergence education adoption and implementation.
- **Regional, State, and Community Based Organizations** should identify and address barriers in effective convergence education as they arise, as well as serving as champions for support of convergence education.
- **Tribal, State, and Local Education Agencies and PK-12 Education Leaders** should promote and provide professional development opportunities for developing and implementing convergence education and offer resources to enable execution of convergence education both within and beyond the classroom.
- **Institutes of Higher Education, especially Educator Preparation Programs,** should develop and offer methods courses for pre-service teachers, and professional development for in-service teachers, that embrace transdisciplinary and convergence education. These should specifically provide the opportunity for pre-service teachers to gain experience blending learning across disciplines in order to solve compelling socio-scientific problems to ensure STEM confidence and identity in educators.
- **Higher Education Academic Administrations and Institutions** should develop hiring practices and promotion policies that include explicit guidelines to recognize the importance of both convergent and transdisciplinary research and scholarship.
- **STEM Education Ecosystems** should collaborate on the imperatives listed by specific stakeholder types above, and work to holistically implement efforts in a collaborative and supportive manner. The use of shared resources, stakeholders, and intended outcomes presents the opportunity to achieve the common goal towards greater convergence education across the nation.

[52] National Research Council (2014). Convergence: Facilitating Transdisciplinary Integration of Life Sciences, Physical Sciences, Engineering, and Beyond. Washington, DC: National Academies Press. https://doi.org/10.17226/18722.
[53] https://www.nsf.gov/crssprgm/nano/reports/ConvergenceEducation.pdf

Appendix 1: Research Articles on Transdisciplinary Learning and Convergence Education

Literature review conducted by representatives of the Smithsonian Science Education Center in order to identify existing research articles on transdisciplinary learning and convergence education. This list is also available at: https://ssec.si.edu/transdisciplinary-Learning.

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Bartholomew, S. R., & Strimel, G. J. (2018). Factors Influencing Student Success on Open-Ended Design Problems. International Journal of Technology and Design Education, 28(3), 753–770. https://doi.org/10.1007/s10798-017-9415-2

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