STEM Education as a Paradigm Shift: What Research says about STEM Education

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STEM Education as a Paradigm?

- **STEM Education** around the World: 184 out of 193 UN Member Countries – teach STEM education.
- **STEM Education** idea – Not NEW in Sciences but NEW in School Science Curriculum

⸎ Biochemistry – 19 century | Molecular biology – 20 Century

⸎ 19C, 20C's Culture – Nuerath, Popper, Bloomberg

- **Why STEM education?**
  In part, driven by dissatisfaction with traditional approaches to science and mathematics education in the United States.

- 9 Countries: Mali, Monaco, Syria, Vanatu, Saint Lucia, Guinea, etc.

Café Central, Vienna

“The Vienna Circle”

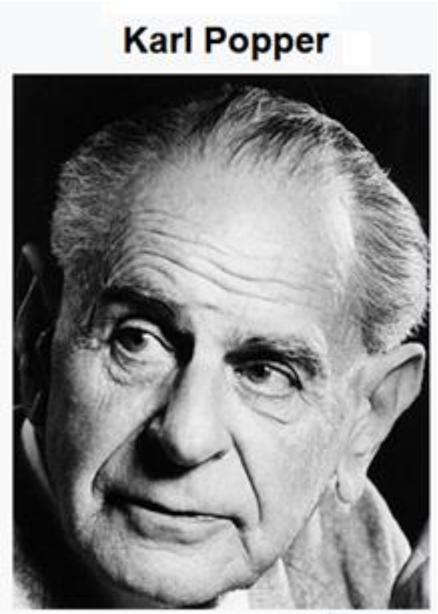
“Enormous amount of integration works done”

Popper; Neurath Blumberg, Morris, politicians, architect, businessmen, scholars from China, Argentina, Italy, UK, USA, etc.

Paradigm

"progress of scientific knowledge" by falsification vs. paradigm shifts

Karl Popper vs. Thomas Kuhn



A theory in the empirical sciences can never be proven, but it can be falsified

Scientific truth cannot be established solely by **objective criteria** but is defined by a **consensus** of a scientific community

Paradigm

“Einstein’s Special Relativity”

Time/Space/Consistency of the speed of light

Published
1905

Three Tests by others
1881, 1932, 1938

Accepted
1938

Consensus of a scientific community

History of STEM Education in the U.S.

Project Synthesis
1980

STS
1980s

STEM
1990s

Present
2013--

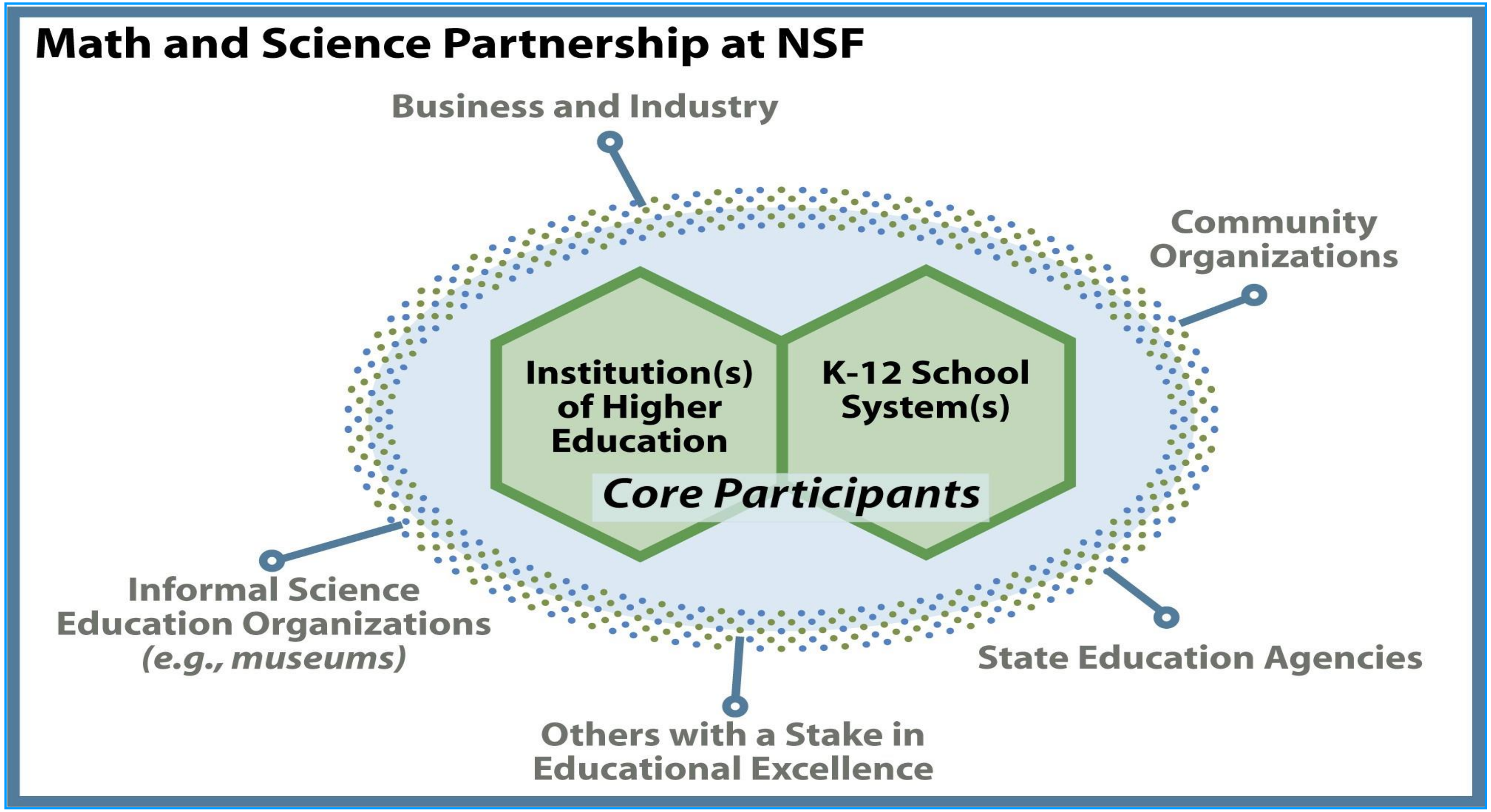
Standards:
NSES (1996)

Standards:
NGSS (2013) -
STEM

STEM – Greater emphasis on new curricular and instruction – Numerous new instructional materials, programs, and specialized schools are emerging

Project Synthesis (1980)

- “Relevance and Effectiveness of Instruction”
- Five Teams; in Biology Team - R Bybee and RE Yager
- Difference between the **desired states** and the **actual states** in 6 areas - **Science, Technology and Society (STS):** “While the impact of science and technology on our day-to-day lives can only be more obvious today than ever before, the value attached to traditional school science programs seems to be on the decline” (p. iii).



Through the Math and Science Partnership program, NSF awarded competitive, merit-based grants to teams composed of institutions of university and K-12 school to support their partnership.

145 Funded MSP Projects (7 years, NSF)

12 Comprehensive Partnerships
(FY 2002, FY 2003)

36 Targeted Partnerships
(FY 2002, FY 2003, FY 2004, FY 2008)

23 Institute Partnerships
(Prototype Award in FY 2003, FY 2004, FY 2006, FY 2008, FY 2009)

19 MSP-Start Partnerships
(FY 2008, FY2009)

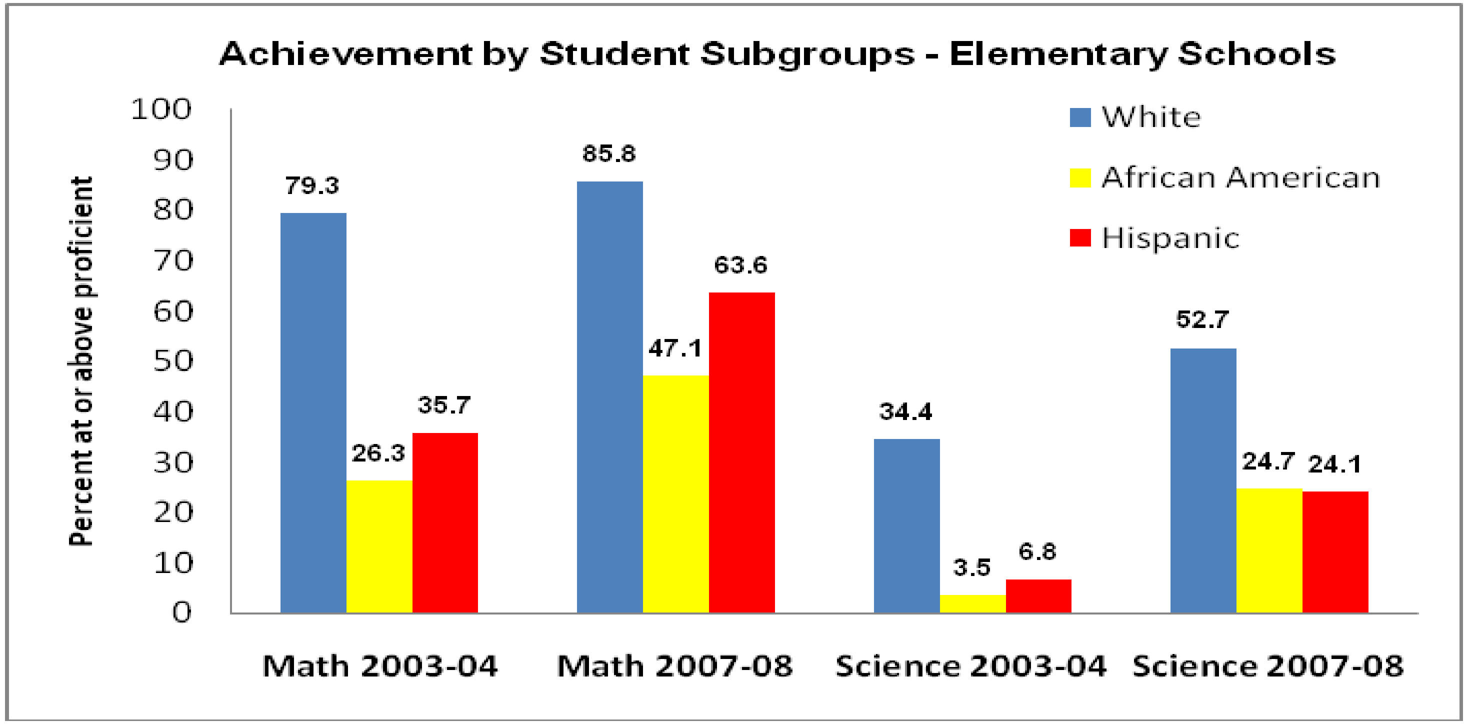
6 Phase II Partnerships
(FY 2008, FY 2009)

49 RETA projects (Research, Evaluation, Technical Assistance)
(Design Awards in FY 2002, FY 2003, FY 2004, FY 2006, FY 2008, FY 2009)

Examining Student Achievement

- Year-by-Year Trend Analysis
- Matched comparisons
- Meta-analysis pre/post assessments

Closing the Achievement Gap



Standards
(National Science Education Standards, NRC, 1996)

1. Unifying Concepts and Processes in Science;
2. Science as Inquiry;
3. Physical Science;
4. Life Science;
5. Earth and Space Science;
6. **Science and Technology;**
7. Science in Personal and Societal Perspectives;
8. History and Nature of Science.

(NRC, 1996, p. 6)

Standards (NGSS, 2013): Engineering

- **Scientists:**

  1. Ask questions
  2. Develop/use models
  3. Plan/execute investigations
  4. Analyze/interpret data
  5. Use math and computational thinking
  6. **Construct explanations**
  7. Engage in argument from evidence
  8. Obtain, evaluate, communicate information

- **Engineers:**

  1. Define problems
  2. Develop/use models
  3. Plan/execute investigations
  4. Analyze/interpret data
  5. Use math and computational thinking
  6. **Design solutions**
  7. Engage in argument from evidence
  8. Obtain, evaluate, communicate information

STEM Education as a Paradigm

Special Relativity 1905

Project Synthesis 1980

Consensus

Accepted 1938

Standards: NGSS (2013) - STEM

STEM Education: Definitions

- STEM education as **an approach** that teaches scientific and mathematical concepts with the **integration** of technology and engineering from K-12 (**Bybee, 2010)**.
- “STEM education includes **approaches** that explore teaching and learning among any **two or more** of the STEM subject areas, and/or between a STEM subject and one or more other school subjects” (**Sanders, 2009).**
- “STEM education is **an approach** to learning that removes the traditional barriers separating the four disciplines and **integrated** them into real-world, rigorous, relevant learning experiences for students” (**Vasquez, Sneider, & Comer, 2013**).
- “STEM education is an **interdisciplinary approach** to learning where rigorous academic concepts are coupled with real-world lessons as students apply science, technology, engineering, and mathematics in contexts that make **connections** between school, community, work, and the global enterprise enabling the development of STEM literacy and with it the ability to compete in the new *economy”* (**Tsupros, et al., 2009**).

Key (Common) Ideas of STEM Education

(1) Real-world Problems, Careers in STEM fields
(2) Approaches
(3) **Integration**
(4) STEM Literacy

Challenges with STEM Education Definitions

- Relatively little attention:

(a) How and to what degree the four subject areas are integrated in schools

(b) What impact on learning such integration might have.

Integration Terminology

- **Increasing levels of integration (adapted from Vasquez et al., 2013)**

Form of integration	Features
1. Disciplinary	Concepts and skills are learned separately in each discipline.
2. Multidisciplinary	Concepts and skills are learned separately in each discipline but within a common theme.
3. Interdisciplinary	Closely linked concepts and skills are learned from two or more disciplines with the aim of deepening knowledge and skills.
4. Transdisciplinary	Knowledge and skills learned from two or more disciplines are applied to real-world problems and projects, thus helping to shape the learning experience .
Vasquez, J., Sneider, C., & Comer, M. (2013). STEM lesson essentials, grades 3–8: integrating science, technology, engineering, and mathematics. Portsmouth, NH: Heinemann.	

History of Integrated Curriculum

- **Efforts** to integrate curriculum and instruction in the U.S. – a long history
- 90 years ago: Progressive Education Movement of the 1930s and 1940s (Vars, 1991).
- 30 years ago: Standards-based Education Reform Movement- Recognizing the Value of integration in STEM.
  --*Benchmarks for Science Literacy* defined science as "basic and applied natural and social science, basic and applied mathematics, and engineering and technology, and the interconnections—(AAAS, 1993, p. 321).
  --Both *Benchmarks* and the *National Science Education Standards* (NRC 1996) called for student learning related to "technology and society" and "technological design"—in *science* classes. "Practices o Science and Engineering" NGSS (2013)
  --*Standards for Technological Literacy* (ITEA, 2000): Learning goals related to engineering design and emphasize the need for students to understand technology's connections to science, engineering, and mathematics.
- 30 years ago: Integrated Curriculum at Illinois State University (NSF funded 1990)

NRC – Integrated Curriculum, 2013

- ***Teaching***: Teaching STEM in a more connected manner, especially in the context of real-world issues, can make the STEM subjects **more relevant** to students and teachers.
- ***Outcomes***: Enhance motivation for learning and improve student interest, achievement, and persistence. And these outcomes will help address calls for greater workplace and college readiness as well as increase the number of students who consider a career in a STEM-related field.
- ***Standards**:* Both the *Common Core State Standards for Mathematics* (CCSSM) and the *Next Generation Science Standards* (NGSS) have called for **more and deeper connections** among the STEM subjects
- ***NGSS*** explicitly includes **practices** and core ideas from engineering and science, raising the **expectation** that science teachers will be expected to **teach science and engineering in an integrated fashion**.

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- **STEM Education as a Paradigm**
- **Research Agenda in STEM Education**
- **What Research Says about STEM Education**
- **Implications of the Research**

Research Agenda in STEM Education

-National Academy of Engineering (NAE) and National Research Council (NRC), 2014-

Status: **Little research** on how best to teach or on what factors make integration more likely to increase student learning, interest, retention, & achievement in STEM fields.

Need to:

- Identify and characterize existing **approaches** to integrated STEM education, both in formal and after-/out-of-school settings,
- Review the evidence for the **impact** of integrated approaches on various student outcomes.

Challenges of STEM education research

- ***Confusing landscape***: a range of different experiences that involve some degree of connection.
- ***STEM experiences:* I**n one or several class periods in a single course or in and out-of-school activity.
- ***Each problem of integrated STEM education***: different planning approaches, different resource needs, different implementation challenges, and outcomes.
- ***Framework***: Goals, Outcomes, Nature of integration, and Implementation.

Research on goals, outcomes, nature of integration, and implementation.

- ***Goals*****: B**uilding STEM literacy and 21st century competencies; **D**eveloping a STEM-capable workforce; and **B**oosting interest and engagement in STEM.
- ***Outcomes*****: L**earning and achievement; STEM **c**ourse taking; STEM-related **e**mployment; **d**evelopment of “STEM identity”; and the **a**bility to transfer understanding across STEM disciplines.
- ***Nature and scope of integration*****: w**hich subjects are connected; **w**hich disciplines are dominant; and the **d**uration, **s**ample size, and **c**omplexity of a project.
- ***Implementation***: **I**nstructional designs involving problem-based learning and engineering design; the type of educator supports present, such as pre- and in-service professional development and development of professional learning communities; and adjustments to the learning environment, such as extended class periods, extended lesson planning, team teaching, and partnering between STEM educators working in and outside of schools.

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What Research Says about STEM Education

- ***Research* on the Impacts of STEM Education** in **two areas:** (a) Learning and achievement, and (b) Interest and identity.

--------------- (a) Learning and Achievement ----------------

⸎ ***Integration of STEM concepts and practices*** has the promise to lead to increased conceptual **learning** within the disciplines. However, the positive impact on **learning** appears to be different for science and mathematics, with less evidence of a positive impact on mathematics outcomes.

⸎ ***Science and mathematics***: the impact on learning and achievement depends on the **approach** to integration and the kinds of **teacher supports** to students.

⸎ ***Engineering and technology:*** Integrated STEM education also shows promise of supporting knowledge gains in E & T. The small number of studies; small sample sizes; reliance on pre- and post-study designs – limit a full interpretation o these findings.

Cont.

--------------- (b) Interest and identity ---------------

⸎ ***Integration of STEM concepts and practices: S***upport interest development, but research studies vary considerably in quality and often do not take into account the different phases of interest development, limiting what can be concluded.

⸎ ***STEM education experiences:* P**rovide opportunities for students to engage in STEM in ways that potentially transform their identities among students struggling in STEM classes AND historically underrepresented group in STEM programs.

⸎ **Challenge with studies on identity in STEM education:**
Few and most of the studies are qualitative in nature.
Outcomes are more measured in after- and out-of-school settings than in formal classrooms.

Implications of Research for the Design of Integrated STEM Education

STEM Learning in terms of 'How people learn':

- Integration may be effective because basic qualities of cognition favor connected concepts over unconnected concepts, so they are better organized for meaning making.

- **Social and cultural experiences** working with each other and actively engaging **in discussion**, **joint decision making**, and **collaborative problem solving** may be particularly important in integrated learning. Some **social processes** can support learning; **Scaffolding**, **peer collaboration** can help students to learn and advance their learning.

Cont.

Use of real-world situations or problems:

- ***Benefit:*** Bring STEM fields alive for students and have the potential to deepen their learning,
- ***Challenge***: Pose challenges to students because the use of detailed concrete situations can prevent students from identifying the abstract structural characteristics that are needed to transfer their experiences to other settings.

Three Key Implications for the design of integrated STEM education initiatives

1..Integration should be made explicit.

⸎ Research shows that **integration** across representations and materials and multi-day units, is not spontaneously made by students and therefore cannot be assumed to take place.

2..Students' knowledge in individual disciplines must be supported.

⸎ Connecting ideas across disciplines is challenging when students have little or no understanding of the relevant ideas in the individual disciplines.

⸎ Students do not always or naturally use their disciplinary knowledge in integrated contexts.

⸎ STEM experience should provide intentional and explicit support for students to build knowledge and skill both within -- and across disciplines.

3.. More integration is not necessarily better.

⸎ The potential benefits and challenges of making connections across the STEM subjects suggest the importance of a **measured, strategic approach** to implementing STEM education that accounts for the potential tradeoffs in cognition and learning.

Reviewing the Research:
A Framework for STEM Education (NAE, NRC, 2014)

GOALS for Students
- -STEM literacy
- -21st century competencies
- -STEM workforce readiness
- -Interest and engagement
- -Making connections

GOALS for Educators
- -Increased STEM content knowledge
- -Increased pedagogical content knowledge

NATURE AND SCOPE OF INTEGRATION
- -Type of STEM connections
- -Disciplinary emphasis
- -Duration, size, and complexity of initiative

STEM Ed

OUTCOMES for Students
- -Learning and achievement
- -21st century competencies
- -STEM course taking, educational persistence, and graduation rates
- -STEM-related employment
- -STEM interest
- -Development of STEM identity
- -Ability to make connections among STEM disciplines

OUTCOMES for Educators
- -Changes in practice
- -Increased STEM content and pedagogical content knowledge

IMPLEMENTATION
- -Instructional design
- -Educator supports
- -Adjustments to the learning environment

Review of research on STEM Education

Two key outcomes

(a) Learning and Achievement

(b) Interest and Identity

Research on LEARNING AND ACHIEVEMENT

- **Research on students' achievement**:

ǂ **Subject-specific knowledge**, problem-solving ability, and ability to make connections between domains is not extensive.

ǂ Concerns are with the **design of studies**.

ǂ **Integration** can lead to improved conceptual learning in the disciplines but that the effects vary depending on the nature of the integration, the outcomes measured, and the students' prior knowledge and experience.

Cont.

- **Assessment:** Most studies of STEM learning lies in each discipline singly and do not measure students' ability to make connections across disciplines or their proficiency of problem solving.
- **Assessment:** Assessment instruments on integration are rare because theories and tests have generally focused on content area–specific concepts and procedures.

Integrating Mathematics and Science

- Studies on integrating mathematics and science are Berlin and Lee 2003, 2005; Czerniak et al. 1999; Hurley 2001; Pang and Good 2000.
- Czerniak et al. (1999): Very **few empirical studies** of the integration of mathematics and science; many of the published articles were theoretical in nature.

Cont.

- **Hurley (2001):** Meta-analysis of 31 studies that compared integrated mathematics and science instruction to a nonintegrated control group.
- **Hurley (2001)** found **positive effects** of integration on scores in both math (ES = .27)2 and science (ES = .37), which is consistent with other meta-analyses that report small to medium positive effects of integration (Hartzler 2000).
- **Effect size varies** by subject: Effect size for math achievement (ES = .07) was lower than the effect for science achievement.

Learning Science and Mathematics in the Context of Engineering Design

- **Engineering is Elementary (EiE)** estimates that its curriculum has reached 4.1 million students and has been used by 52,000 teachers (Christine Cunningham, Museum of Science, Boston, personal communication, August 1, 2013).
- **Project Lead the Way (PLTW)** estimates that 5,500 schools offer at least one of its programs each year, enrolling between 400,000 and 500,000 students annually (Jennifer Cahill, PLTW, personal communication, August 7, 2013).

Cont.

- Overall, using Design-based approaches, **the effect** of learning science and mathematics through engineering design was **positive** on students learning in science and mathematics (NAE/NRC, 2009).
- **Project Lead the Way (PLTW**): **Mixed results**: All **low-incom**e families students showed significant overall gains in mathematics and science achievement scores between 8th and 10th grade. **High-income** families students showed small gains in mathematics achievement but no improvement in science **(**Tran and Nathan, 2010a, 2010b).

Cont.

- **These two studies** found that Enhancing math achievement through integration with other disciplines is difficult to do.
- **Students need teacher’s support** to see how specific mathematics concepts and skills are integrated with the engineering activities.
- **These studies also fail** to show substantially larger gains for students participating in project-based engineering courses.

Cont.

- **Students may not spontaneously make connections** between the devices being designed and the related scientific concepts (Crismond 2001; Kozma 2003; Nathan et al. 2013)
- Students tend to focus on **aesthetic aspects** of design (Crismond 2001; Penner et al. 1998).
- Crismond (2001): **Expert vs. nonexpert**: Experts recognize opportunities to connect with science ideas, but nonexpert designers miss them.

Learning Science and Mathematics in the Context of Engineering Design .. Cont.

- **Scientific knowledge** is gained through engineering design when the activities are highly contextualized and explicitly designed (Fortus et al. 2004, 2005).
- **This approach can be effective** if concepts are introduced when students engage with the design activity (Baumgartner and Reiser 1997; Fortus et al. 2004; Mehalik et al. 2007) or when design failure provokes conceptual change as students redesign an artifact to meet a goal (Lehrer et al. 2008).

Learning Mathematics in the Context of Technology

- **Stone et al. (2008):** Promising results on mathematics-enhanced career and technical education (CTE) courses in high school.
- **Burghardt et al. (2010):** Promising results on infuse mathematics in a 20-day middle school engineering/technology (ETE) course.

Learning about Engineering and Technology

- Very few studies but **pilot studies** conducted as part of a **large-scale curriculum intervention in New Jersey** show some promising results.
- **Pilot of a Large-Scale Study *showed*** promising results.
  Engineering Our Future New Jersey (EOFNJ) is a collaborative effort of
  --Stevens Institute of Technology,
  --New Jersey Department of Education,
  --National Center for Technological Literacy (NCTL) at the Museum of Science, Boston,
  --Exemplary technology and engineering curricula, such as *Engineering is Elementary* (EiE) and *A World in Motion*
  --**Intervention: All K–12 students in New Jersey experience engineering curricula with a focus on innovation fo 5 years**, as a required component of their elementary, middle, and high school education.
  --**Pilot studies** were conducted at each school level.

Summary of the impact on “Learning and Achievement”

- **Integration of STEM concepts** in applied settings can yield increased conceptual learning in the disciplines (Limitation -- Too many inconsistencies in implementing or assessing STEM programs).
- **Student learning** appears to differ for science and mathematics—it is less evident for mathematics outcomes
- **Integration** shows improved results on assessments of specific concepts used the intervention, but not on general mathematics or science achievement tests administered by states.
- **Lack of consensus** upon definition for integration**. So, i**t is difficult to assess how different approaches to integration support learning.

Research on INTEREST AND IDENTITY

- Fostering the development of students' interest and identity in STEM is an important potential outcome of integrated STEM experiences.
- Interest and identity are thought to lead to continued engagement in course selection, college major, and career path.

Evidence that Integrated STEM Supports Development of Interest and Identity

- Several programs support the development of interest, identity, and continuation in STEM.
- Measures of interest in STEM are more common in studies of out-of-school programs.
- Measures of the identity development is less common.

INTEREST

- **Interest Studies**: STEM programs can support the development and maintenance of interest in STEM fields.
- **Typical Programs or Interventions**: School-based projects and curriculum units, afterschool programs, and summer camps.
- **Positive effects**: A school-based engineering project for 6th and 7th graders showed positive effects on students' attitudes (High et al. 2010).

Cont.

- **Out-of-school program: E**valuation of the "**Techbridge**" program (2000 to 2007) though surveys.
- Results:
  (a) Around 90 percent of the girls (N=367) said Techbridge had increased their interest in STEM;
  (b) What got them most interested in STEM: Hands-on projects (70%) and field trips (16%) (Ancheta 2008).

Cont.

- **Enrichment program** for high school youth, integrating engineering with biology concepts in a health care context--**positive effects** on interest (Monterastelli et al. 2011).
- **All-girl summer camp** with a STEM focus: **Positive effects** on interest (Plotowski et al. 2008).

Cont.

- **Out-of-school program** (“Proect Exploration” in Chicago) for middle school–aged girls and minority students: **Greater interest and confidence** in science (Chi and Snow 2010).
- Four studies of 4-H robotics programs showed somewhat **mixed results** regarding attitude (Baker et al. 2008).
- **Out-of-school program**: Students engaged in computer programming and engineering using robotic kits: Improvement in their attitudes toward science and technology (Martin et al. 2011).
- **Robotics and geospatial program**: Positive attitudes (Nugent et al. 2010).

IDENTITY

- Rahm (2008): Identity development in the context of science clubs for low-income middle school youth.
  Results:
  (a) Integrating **students' histories and cultural backgrounds** with science supports STEM-related identity development.
  (b) **Flexibility** of the program, **the val**ue of doing a project both in and for the community support STEM-related identity development.

Summary of Interest and Identity

- Generally, research on STEM interest showed promising findings; Studies vary in quality.
- The measures of STEM interest are typically not very sophisticated and do not take into account different phases of interest development.
- Many studies use before/after designs without any comparison groups. This is not a very powerful design for determining causal effects, so results are difficult to interpret.

Cont.

- Research on STEM **identity** is at a very preliminary stage.
- **Open-endedness** and **links to students' culture and community** are important in developing STEM identity.

Conclusions on Interest and Identity

- Research on integrated STEM experiences shows promising for supporting both learning in and across the STEM disciplines and the development of STEM-related interest and identity.
- But, the research base is limited in
  (a) the design of the studies
  (b) the student sample size involved in them
  (c) the outcome measures used
  (d) the extent to which research examines the mechanisms underlying learning in integrated STEM contexts.

Conclusions Cont.

- More studies are needed to measure students’ ability to make connections across disciplines.
- Few studies focus on the development of interest and identity in formal educational settings.
- More studies are needed to show more connections with engineering and technology.

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Implications of the Research reviewed so far

- Research on integrated STEM is at the preliminary stages and there are few large-scale studies that systematically compare different approaches to integration.
- Conduct research on cognition, learning, and teaching to formulate hypotheses about how to design effective integrated STEM learning experiences.
- Conduct research on how people learn in order to determine how integrated experiences in STEM might support learning, thinking, interest, and identity development, and, conversely, why they might do little to change students' attitudes, thinking, and behaviors.

Integrated Experiences and How People Learn

- Draw on a substantial body of research on cognition and learning to explore the mechanisms by which integration might support, or be an obstacle to, learning within and across the STEM disciplines_by using cognitive psychology, the learning sciences, educational psychology, curriculum and instruction.
- How and why integrated STEM experiences can support improvement in learning and thinking where they might pose difficulties for learners, and how they can be designed to be more effective.

Conclusion

- Based on findings from studies on learning and teaching across research traditions informed by situative, sociocultural, cognitive, pragmatist, and constructivist perspectives, it is possible to hypothesize both advantages and disadvantages for learning from integrated experiences in STEM education.

Thank you