

A Look at Relationships (Part I): Supporting Theories of STEM Integrated Learning Environment in a Classroom - A Historical Approach

Tomoki Saito, Ilman Anwari, Lely Mutakinati, Yoshisuke Kumano

Graduate School of Science and Technology, Shizuoka University, Japan

E-mail: tomsent0@gmail.com

Authors note: This research was supported by a grant from MEXT/JSPS KAKENHI Grant Number: 23300283, and a special grant for the Local Supporting Project from Shizuoka University. The field was provided by Shizuoka Science Museum Ru · Ku · Ru, and figures were developed by Hoko Sudo.

ABSTRACT

In this article, the authors address STEM pedagogies that relate to “integration” issues and to their implementation. Referring to past discussions on transdisciplinary teaching and learning (“transdisciplinarity”), the authors claim that STEM integration might lead to synergy between each of four disciplines, and the interaction of those learnings might have mutual benefits as well as disadvantages. Hence, although educators often find it difficult to leave discrete disciplines in which they studied, learning in an integrated environment that focuses on student-centered learning, could or should differ from teaching in traditional classes. Learning in the STEM Integrated Learning Environment has certain features: 1) learning is not necessarily included in and assessed by disciplines as in traditional classes; 2) learning within and across networks of learners has relationships beyond STEM disciplines; and 3) thus, the environment would be structured by vectors of those relationships. If so, teachers are expected to prepare for interactions among STEM areas of learning.

Keywords: STEM Integration, System of Learning, Practices, Transdisciplinarity

This article’s intent is to add a theory about learning characteristics in STEM integrated classes. From a synthesis of some prior theories, the authors concluded that integration would have a structured “system of learning” according to interactions and relationships within STEM learning. In the following sections, by reviewing prior theories individually, the authors explain how this system of learning would appear, focusing on relationships among STEM areas that are important for STEM activities and have both student-centered learning in real-world contexts and standard alignment of science for all. In turn, the authors suggest the theory that would support their STEM effort in Japan. STEM integrated learning is not necessarily included in traditional education disciplines, but it can support a variety of learning by students and teachers. By discussing the theory in this article, the authors aim to contribute to the STEM effort to foster innovative, resourceful individuals who will engage fully in a highly technological world.

STEM for All - The Definition of STEM is Ambiguous

Many STEM practitioners might pose the following questions: “What is STEM integration?” “How does STEM integration differ from traditional science education?” In other words, although we call it STEM, the class we structured and implemented did not necessarily reflect the natural interconnectedness of the four STEM areas (Katehi, Pearson, & Feder, 2009). This results from an unclear definition of STEM education and the difficulty

in establishing how STEM learning should appear in the classroom. Because literature describing the theoretical framework for integration itself is limited (Roehrig, 2012), some descriptions were not clear (Wang, 2011). Although there were many calls for a definition, once one had been stated, few agreed with it (Bybee, 2013). Thus, STEM cannot be a scientific term where scientists choose to replace a series of complex observations with a single new word (Yager, 2015).

Against this background, the authors focused on integration and intended to become armchair theorists by depending on the few extant descriptions of integrated learning and to take modest, positive steps because, as mentioned in a previous article, STEM lesson planners require scaffolding to accelerate their STEM pedagogies (Saito, Gunji, & Kumano, 2015). Thus, this set of articles should become a testing ground where all STEM practitioners and researchers can discuss what STEM integration is, how it manifests in their classrooms, and how it benefits students. Importantly, besides defining only STEM education, we define the appearance of implemented integration based on limited but related and substantive theories. Of course, these theories should support implementation in future classes and provide cases in this set of articles that will serve as examples for classroom teachers.

However, educators face a paradox. Although we need to define exactly what we teach for class preparation and standards alignment, student-centered learning comes from students' interests, not from preparation of that discipline. Some educators, e.g., Vasquez, Sneider, & Comer (2013), who have written on this point in STEM literacy, writing about literacies in each STEM discipline, claimed that combined "STEM literacy" should not distinguish whether students have this literacy because if we define it as a clear statement, we create a gap. Even if we had set goals of science education for utilizing science (or engineering), responsibility for science-related societal issues, or career awareness, the goal that schools commonly set remains acquisition of academic knowledge (Yager, 1986). Hence, we could call students' learning "STEM literacy", but it should not be so. Definition and evaluation, in other words, "grading", causes gaps and makes students less motivated and interested (Kohn, 1994). Hutchins (1968) and Adler (1982) have discussed this point: Hutchins claimed that no one curriculum supports a great variety of students. Adler, on the other hand, argued that a course of study is needed to support equal education for all, with no exceptions. If we rethink these notions in the 21st century, learning should be specific for learners, but goals have to be possible in order to encompass idiosyncrasies. Thus, the authors once tentatively called it the "appearance" of a STEM integrated learning environment and attempted to discover, as their research question, what interactions or relationships would emerge when STEM learning is actually integrated. However, this is meant not to grade students' learning, but to help teachers understand their work with a class and to help them prepare well for student-centered learning.

Classification of STEM Education

We are not going to attempt to define STEM, but rather identify several directions of STEM efforts. For example, from the STEM Education Act of 2015, we find three classifications of STEM Education: Single STEM Discipline, Multi Disciplines, and Integrative STEM Initiatives (House of Representatives, 2015). If we think of these as student-centered notions, we can identify the integrative approach's importance.

Similar to this classification, Fogarty (1991) had already indicated ten methods of curriculum integration: Fragmented, Connected, Nested, Sequenced, Shared, Webbed, Threaded, Integrated, Immersed, and Networked; he classified these methods into three categories: Within Single Disciplines, Across Several Disciplines, and Within Learners and Across Networks of Learners. These classifications imply where STEM learning will be

integrated. First, where learning is integrated within single disciplines, integration can appear in traditional classes that discretely separate subjects. Second, if STEM learning is integrated across several disciplines, it might lead to teachers' cooperation or subjects' reconstruction; hence, integration should occur in teachers' meetings or during curriculum development. The third classification seems a better fit with the student-centered notion; when integrated within learners and across networks of learners, integration would occur in students' learning, in their communities, or in their brains. These models also suggest that STEM integrations can construct an "Ecology of Learning" (Bybee, 1997; Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003) or a "System of Education" (Pestalozzi affected Huxley, 1899 and Spencer, 1864; as cited in DeBoer, 1991, p. 21¹), in which integrations are ubiquitous in the learning environment (Olson & Labov, 2014). Here we propose and name it a "STEM Integrated Learning Environment" (Saito & Kumano, 2015).

If STEM works as a system of learning, how can we predict interrelationships among its parts from a description of system characteristics? From the different layers of perspective, we could find some suggestions about what might occur when the parts are integrated. Past educational standards have described systems in that if parts of social and/or natural systems are joined, they can do things they could not do alone (AAAS, 1993; MOEA, 2002). These features of systems have implications for integration of STEM learning: Each part of STEM in an integrated environment would have mutual synergy and appear as certain different functions as a subsystem of learning. Students and teachers must also be included as parts of the system. So, then, how can STEM be an integrated learning environment as a System of Learning?²

Student-Centered Learning and Transdisciplinarity

As many STEM related articles discuss, one reason STEM invites integration is it can provide "real-world contexts" (Bybee, 2011, 2013; Fensham, 2009; Katehi et al., 2009; PCAST, 2010, 2012), and this idea is not new in educational discussions. Especially in engineering education, at least since the 1950s, an important topic has been to prepare students to be real-world problem solvers (Bailey, 1978; Felder, 1988; Osborn, 1957). Additionally, from the perspectives of "Science, Technology, and Society" (STS) and the nature of science, discussions took place about how science and society affect each other (Gibbons, 1994; Hurd, 1958, 1991, 1998; Kuhn, 1962; McComas, Almazroa, & Clough, 1998; Yager, 1980, 1996), and theories for the basis of integration were developed. Especially in the 1980s and 1990s, integration and redefinition of disciplines were discussed in terms of STS (Bybee, 1987; Good, Herron, & Renner 1985), sometimes called SMET: Science, Mathematics, Engineering, and Technology (D'Ambrosio, Black, El-Tom, Matthews, Nebres, & Nemetz, 1992). According to those studies, we can also find some suggestions for describing learning with trans-disciplinary problems (issues). Those who struggle with a trans-disciplinary problem will work with those in other disciplines or with other stakeholders beyond the discipline. In this situation, because of the problem being decided by the application context, people work in different theoretical frameworks, methods, and styles of research from individual disciplines and often do not return to the rigor of their own disciplines.

¹ They had separated human activities into several major disciplines, but they also felt less relevance for one's lives (DeBoer, 1991).

² This term, system of learning, is sometimes used by language educators. In addition, educators in science education have already used the notion of ecosystem (Bybee, 1997; Olson & Labov, 2014). Although educators usually explain the system in a broader context to include various stakeholders, the authors focused instead on a minimum example of real-world context, i.e., "System of STEM learning" in the STEM integrated learning environment according to the notion of "system". In addition, it is important to note that results of observation can be only a contemporary slice of the system.

If we translate these theories into classroom terms, we can find the meaning of real-world context as a learning environment. When students as problem solvers work with real-world problems, they naturally integrate learning activities. In this situation, the role of each STEM discipline would differ from traditional fragmented learning. Hence, students should be “doing” science with other T, E, and M learning (Yager, 2014), rather than learning the result of each discipline. This description must be shared as a characteristic of STEM integrated learning environments for those who have worked in STEM classes. As a matter of fact, in the authors’ implementation (Saito, Gunji, & Kumano, 2015), engineering activities did not necessarily meet science standards, like the Next Generation Science Standards (NGSS Achieve, 2013) in the United States or the national curriculum called Course of Study by the Ministry of Education Culture, Sports Science and Technology (MEXT, 2008) in Japan. And, if so, to what extent do they differ? Although this was debated in the STS era, particularly between science and technology (Penick, 1984), how can we identify interactions among the S, T, E, and M areas of learning within and across networks of learners?

The New Framework and Integration

If we think from a perspective as in those related theories in previous sections, new frameworks resemble integration of several educational aspects.

As Kumano (2012, 2014) revealed in *A Framework for K-12 Science Education* (NRC, 2012), engineering was placed in scientific activities and scientific “practice” (Michaels, Shouse, & Schweingruber, 2007) and used as a corresponding word for scientific “inquiry” (Schwab, 1962). According to Bybee (2011), scientific inquiry is one of the forms of scientific practices that aim at proficiency, learning subjects thoroughly at school, and applying knowledge for an objective, for example. According to this meaning, science in the STEM integrated learning environment has the potential to change its appearance to practice, in addition to inquiry. What kind of change would this be? How would it work for students’ learning? Can it conserve the benefit of inquiry? Such discussions might encompass integration of interest and effort, as Dewey (1913, 1938) believed. In Dewey’s sense, effort does not mean effort to remember learning content, but rather to satisfy a need of their (learners’) interest (Matsuoka, 2007). As Dewey suggested, does practice work as effort even if the activity does not directly meet interest? Or does it elicit interest from passive/instantaneous pleasure?

From another viewpoint, the corresponding word for inquiry might be “design”. However, it would not mean that design takes place instead of inquiry. In this notion, scientific inquiry and engineering design are involved in practice (NRC, 2012). Thus, practice weaves inquiry and design into its learning activities. Here again, we might have to refer to the suggestion, through the concept of systems, that if those activities are woven together well, the properties of the whole differ from those of its parts (AAAS, 1993, 2009).

We would have to reveal properties of practice as the integration of scientific inquiry and engineering design and need to know how technologies and mathematics relate to the learning in those activities.

Facets to Identify Properties

From inferences extracted from past theories above, researchers need to identify ubiquitous integrations from several facets in teachers’ preparation, learning materials and students’ learning in the educational environment. The authors have focused on teachers’ preparation and learning materials, and have already pointed out that the learning material connects these facets, developing the T-SM-E method to integrate STEM learning (Saito, Gunji, & Kumano, 2015). Those efforts should be continued, and the applications elaborated

in several professional development contexts. On the other hand, what students learned was merely a prediction by educators who had learned about content until implementing actual lessons for students. As the authors explained above, integration has the potential to change roles and interactions of related disciplines in the lesson.

Therefore, in this study, which is explained in this set of articles, the authors seek to define interactions in STEM learning by analyzing contemporary relationships in an integrated STEM class. Interactions of disciplines might be related not only to content (substance), but also to methods (syntax), principles, or warrantability and their differences in each discipline (Dewey, 1938; Phillips & Burbules, 2000; Schwab, 1964). In addition, if what is learned is beyond the traditional disciplines, the authors must consider the need to relinquish the term “discipline” and to focus on the whole appearance of learning with those interactions.

Conclusion

The authors suggest theories for the STEM Integrated Learning Environment. Learning in this environment has the following features: 1) The learning is not necessarily included in and assessed by standards for each discipline as in traditional classes; 2) learning within learners and across networks of learners has relationships beyond STEM disciplines, and 3) thus, the environment should be structured according to the vector of those relationships.

First, in the student-centered learning environment, learning would be heterogeneous, like the cloud in Figure 1 below. Thus, educators would focus not only on the sphere indicated by educators themselves but also on features of students’ learning, which sometimes has greater extent and is denser than teachers’ expectations and other times has less extent and is more diluted than teachers’ expectations.



Figure 1. Heterogeneity of Learning

However, these features could come from relationships in the learning environment. Thus, educators need to gain perspective on relationships that might be mutually effective and may need to intervene in relationships as long as they might be conserved. If we intervene too much, relationships disappear, and students try to apply only within the sphere. That is what we call a “discipline”.

Second, if the students’ learning has a different appearance than expected through various disciplines, that appearance might emerge from the synergy of relationships among STEM learning. Relationships would be decided by the context in which students engage. Thus, even if individual students use/learn the same scientific concepts when developing solutions, the appearance of relationships might differ in each classroom’s context (or in different schools, districts, states/prefectures, or countries). These relationships need not be the point from which to evaluate and grade students’ learning, and we do not suggest to do

so. Instead, these relationships should help assess what students are going to do in their current studies and how they can be supported.

Third, if we focus on relationships to assess students' learning, we can infer students' interests and how they think and feel about current learning activities in order to plan the next. Interests would have vectors to other STEM learning as the appearance of those relationships (Figure 2), and they might become energy for structuring the STEM integrated learning environment. Those vectors will certainly become the output from the system of learning.

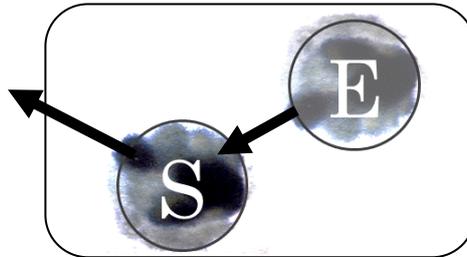


Figure 2. The Relationships in the STEM Integrated Learning environment

On this point, we can find suggestions from past educators. Barr (1994, p. 244) cited Dewey's (1913) inference about the relationship between practical (engineering) activities and scientific inquiry. If students are given sufficient chances to explore scientific problems, they spontaneously move from their goal (engineering problem) to a search of causal nexus. Like this inference, we can find relationships among STEM activities and how students would conduct learning on their own, by deeply and carefully observing the class. Just as Dewey's inference was later confirmed by Schauble, Klopfer, and Raghavan (1991), relationships might be confirmed by empirical research. However, relationships should be understood by professional classroom teachers as well. Indeed, we need to improve collaboration between teachers and researchers.

Finally, based on the theory of a STEM Integrated Learning Environment, certain research questions are posed to improve the theory itself and its methodology:

- 1) If STEM integration can be observed, what kinds of relationships can we find in each case?
 - 1.1) In terms of standard alignment, do those relationships differ between public school programs and informal settings?
- 2) Is it possible to describe observation in the methodology, as in case study research design, as well as by classroom teachers?
- 3) What do these types of learning suggest to improve future implementation?

Although some of the questions are asked in this set of articles, all should be asked and elaborated in many contexts, in which they would be understood and reconfirmed by both teachers and researchers. In this study, educators would make intervention for a systemic reform, rather than a systematic approach (Bybee, 1997; Kitahara & Itoh, 1991) because the results of changing parts of the system in the STEM Integrated Learning Environment are difficult to predict (AAAS, 1993; MOEA, 2002).



Tomoki Saito was a science teacher mainly in junior high school after he got his master's degree in Environmental Education. He is a Ph.D. candidate and studying STEM Education for students' creative learning.



Ilman Anwari was born in Bandung, Indonesia. He received a B.Ed. degree in chemical education from Indonesia University of Education (UPI), Bandung, Indonesia, in 2007, and M.Ed. and Ph.D. degrees in Science Education from Shizuoka University, Shizuoka, Japan, in 2011 and 2014, respectively. Since 2014, he has been a researcher in Shizuoka University, and his main research interests are development of learning materials and lessons for STEM education and Chemical education with the Japanese team.



Lely Mutakinati was born in Sukabumi, Indonesia. She received her B.Ed. and M.Ed. degrees in chemical education from Indonesia University of Education (UPI), Bandung, Indonesia, in 2007 and 2010, respectively. In 2015, she began a doctoral program at Shizuoka University, Japan.



Yoshisuke Kumano is a Professor of science education at Shizuoka University where he teaches Curriculum Studies, Science Education Methods, Seminar in Science Education and related courses. Now, his research is mainly focusing on STEM education reforms for Japan, with Ph.D. candidates and other students in his studies.

References

- Adler, M. (1982). The Paideia proposal: Rediscovering the essence of education. In A. Canestrari & B. Marlowe (Eds.), *Educational foundations: An anthology of critical readings* (Third Edit., pp. 141–149). SAGE Publications, Inc.
- American Association for the Advancement of Science. (1993a). *Benchmarks for science literacy*. American Association for the Advancement of Science. Oxford University Press.
- American Association for the Advancement of Science. (1993b). Research Findings for Chapter 11: Common Themes. Retrieved December 10, 2015, from <http://www.project2061.org/publications/bsl/online/index.php?chapter=15§ion=C&band=11>
- Bailey, R. (1978). *Disciplined creativity for engineers* (2nd ed.). Ann Arbor: Ann Arbor Science Publishers, Inc.
- Barr, B. B. (1994). Research on problem solving: Elementary school. In D. L. Gabel (Ed.), *Handbook of Research on Science Teaching and Learning: A Project of the National Science Teachers Association* (pp. 237–247). Macmillan Library Reference.
- Bybee, R. W. (1987). Science education and the science-technology-society (S-T-S) theme. *Science Education*, 71(5), 667–683. doi:10.1002/sce.3730710504
- Bybee, R. W. (1997). Contemporary reform of science education. In L. Peake & V. Merecki (Eds.), *Achieving Scientific Literacy from Purposes to Practices* (pp. 25–45). Portsmouth, NH: Heinemann.
- Bybee, R. W. (2011). Scientific and engineering practices in K–12 classrooms. *Science Teacher*, 78(December), 34–40.
- Bybee, R. W. (2013). *The case for STEM education challenges and opportunities*. Arlington, Virginia: National Science Teachers Association.
- Cobb, P., Confrey, J., DiSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. *Educational Researcher*, 32(1), 9–13. doi:10.3102/0013189X032001009
- D'Ambrosio, U., Black, P., El-Tom, M., Matthews, M., Nebres, B., & Nemetz, T. (1992). Summer symposium on educating for citizenship in the 21st century. In *Science, Mathematics, Engineering, and Technology Education for the 21st century* (p. 73). Washington D.C.: National Science Foundation Directorate for Education and Human Resources Division of Research, Evaluation and Dissemination.

- DeBoer, G. (1991). *A history of ideas in science education: Implications for practice*. 1234 Amsterdam Avenue, New York, NY 10027: Teachers College Press.
- Dewey, J. (1913). *Interest and Effort in Education*. Boston, MA: Houghton Mifflin Company.
- Dewey, J. (1938). *Logic: The theory of inquiry*. Holt, Rinehart and Winston (1960th ed.). New York: Holt, Rinehart and Winston, INC.
- Felder, R. M. (1988). Creativity in engineering education. *Chemical Engineering Education*, 22(3), 120–125. doi:10.4271/560004
- Fensham, P. J. (2009). Real world contexts in PISA science: Implications for context-based science education. *Journal of Research in Science Teaching*, 46(8), 884–896. doi:10.1002/tea.20334
- Fogarty, R. (1991). Ten ways to integrate curriculum. *Educational Leadership*, 49(2), 61–65.
- Gibbons, M., Limoges, C., Nowotny, H., Schwartzman, S., Scott, P., & Trow, M. (1994). *The new production of knowledge: The dynamics of science and research in contemporary societies*. London: SAGE Publications, Ltd.
- Good, R., Herron, J., Lawson, A., & Renner, J. (1985). The domain of science education. *Science Education*, 69(2), 139–141.
- House of Representative. *STEM EDUCATION ACT OF 2015*, Pub. L. No. 1861 (2015). the United States of America: 42 U.S.C.
- Hurd, P. D. (1958). Science literacy : Its meaning for American schools. *Educational Leadership*, 16(1), 13–52.
- Hurd, P. D. (1991). Why we must transform science education. *Educational Leadership*, 49(2), 33–35.
- Hurd, P. D. (1998). Scientific literacy : New minds for a changing world. *Science Education*, 82(3), 407–416. doi:10.1002/(SICI)1098-237X(199806)82:3<407::AID-SCE6>3.3.CO;2-Q
- Hutchins, R. (1968). *The learning society*. New York: The New American Library.
- Katehi, L., Pearson, G., & Feder, M. (2009). *Engineering in K-12 education: Understanding the status and improving the prospects*. National Academy of Engineering and National Research Council of the National Academies. National Academies Press.
- Kitahara, T., & Ito, S. (1991). *Japanese Systems Thinking* (1st ed.). Tokyo, Japan: Chuo-Keizai Sha.
- Kohn, A. (1994). *Grading: The issue is not how but why*. *Educational Leadership*, (October), 1–11.
- Kumano, Y. (2012). The competencies which aimed by the middle school science curriculum. In S. of J. S. Teaching (Ed.), *Now asking the competencies in school science-viewpoints for the new competencies* (pp. 98–105). Tokyo, Japan: Toyokan.
- Kumano, Y. (2014). Science & Technology Governance and the STEM Education. In Y. Kumano (Ed.), *A fundamental study on the construction of the research theory of science education to develop the science & technology governance* (Final rep., p. 188). Shizuoka, Japan: Shinohara Publishing Co., LTD.

- Matsuoka, Y. (2007). A Study of the Structure of Interrelation between "Interest" and "Effort" in Dewey's Theory of Interest: Focusing on his Argument in Interest and Effort in Education. *Journal of Education in Nihon University*, 42(20070325), 59–74.
- MEXT (Ministry of Education Culture Sports Science and Technology). (2008). *Course of study*.
- Michaels, S., Shouse, A. W., & Schweingruber, H. (2008). *Ready, Set, Science!: Putting Research to Work in K-8 Science Classrooms*. (Board on Science Education Center for Education Division of Behavioral and Social Sciences, Ed.). Washington, DC: National Academies Press.
- Minnesota Office of Environmental Assistance. (2002). *Environmental literacy scope and sequence*. 520 Lafayette Rd. St. Paul, MN 55155-4100.
- NGSS Lead States. (2013). *Next Generation Science Standards: For states, by states*. (Achieve, Ed.). Washington, DC: The National Academies Press.
- Olson, S., & Labov, J. (2014). *STEM learning is everywhere: Summary of a convocation on building learning systems*. Washington, DC: The National Academies Press.
- Osborn, A. F. (1957). *Applied imagination: Principles and procedures of creative problem solving*. Charles Scribner's Sons. (1st ed.). New York: Charles Scribner's Sons.
- Penick, J. E. (1984). Science/Technology/Society. *Focus on excellence* Volume1, Number 5. Washington, D.C.: National Science Teachers Association.
- Phillips, D., & Burbules, N. C. (2000). *Postpositivism and educational research*. Lanham, Maryland: Rowman & Littlefield Publishers, Inc.
- President ' s Council of Advisors on Science and Technology. (2010). *Prepare and inspire: K-12 education in science, technology, engineering, and math (STEM) for America's future: Executive report*. (President's Council of Advisors on Science and Technology, Ed.). Executive Office of the President.
- President's Council of Advisors on Science and Technology. (2012). *Engage to excel: Producing one million additional college graduates with degrees in science, technology, engineering, and mathematics*. Report to the president. Executive Office of the President.
- Roehrig, G., Moore, T., Wang, H., & Park, M. (2012). Is adding the E enough? Investigating the impact of K - 12 engineering standards on the implementation of STEM integration. *School Science and Mathematics*, 112(1), 31-44.
- Saito, T., Gunji, Y., & Kumano, Y. (2015). The problem about technology on the STEM education: Some findings from action research on the professional development & integrated STEM lessons in informal fields. *K-12 STEM Education*, 1(2), 85-100.
- Saito, T., & Kumano, Y. (2015). A Study about Integrated Activities and Its Assessments in STEM Classes. In *Shizuoka STEM Junior Project 2014-2015, A Report for the Future Scientist Program by JST* (pp. 32–50). Shizuoka, Japan.
- Schauble, L., Klopfer, L. E., & Raghavan, K. (1991). Students' transition from an engineering model to a science model of experimentation. *Journal of Research in Science Teaching*, 28(9), 859–882. doi:10.1002/tea.3660280910
- Schwab, J. (1962). The Teaching of Science as Enquiry. In *The Teaching of Science* (pp. 3–103). Cambridge, Massachusetts: Harvard University Press.
- Schwab, J. J. (1964). Structure of the Disciplines: Meaning and Significances. In *The Structure of Knowledge and Curriculum* (pp. 6–30). Rand McNally & Company.

- Thomas, K. (1962). *The structure of scientific revolutions*. London: University of Chicago Press.
- Vasquez, J. A., Sneider, C., & Comer, M. (2013). *STEM Lesson Essentials, Grades 3-8: Integrating Science, Technology, Engineering, and Mathematics*. (K. Bryant, Ed.). Washington, D.C.: Heinemann.
- Wang, H.-H. (2011). *A New Era of Science Education: Science Teachers' Perceptions and Classroom Practices of Science, Technology, Engineering, and Mathematics (STEM) Integration*. University of Minnesota.
- Yager, R. E. (1986). Searching for excellence. *Journal of Research in Science Teaching*, 23(3), 209–217.
- Yager, R. E. (2014). Exemplary STEM programs: Designs for success. In R. E. Yager & H. Brunkhorst (Eds.), *Exemplary STEM Programs: Designs for success* (pp. ix–xiv). Arlington, Virginia: National Science Teachers Association.
- Yager, R. E. (2015). STEM: A focus for current science education reforms. *K-12 STEM Education*, 1(1), 1–4.