From Theory to Practice: Research and Trends in STEM Education

Qingfeng Shen(✉)

School of Education, University of Bristol, Bristol BS8 1TH, UK
`1579676178@qq.com`

Abstract. Coined from the acronyms of Science, Technology, Engineering and Mathematics, STEM advocates an education philosophy that is focused on multidisciplinary integration, practical ability and innovative spirits. By virtue of its significance for training of innovative talents, increasingly more nations have promoted STEM to a national strategy concerning their security, scientific and technological level, and social and economic development. Taking the development process of STEM education in the United States as the research object, this study explores some key literature on STEM education by adopting CiteSpace, while continuing to follow up the new trends of this research subject, so as to identify the evolution footprints and future development direction of STEM education.

Keywords: STEM · Education · CiteSpace · Evolution trajectory

1 Introduction

Given that it becomes impossible to address real-world problems with knowledge from a single discipline, interdisciplinary studies in schools have grown into an increasingly popular and hiking field of interest in educational reforms cross the world. Facing such real-world problems, students are required to integrate knowledge, skills and capacities in different disciplines. In this regard, STEM education is aimed at providing students with a pathway to interdisciplinary understanding, so that they can keep consolidating science, technology, engineering and mathematics together to deliver on coherence and unification across disciplines. For more than 30 years since it was proposed in the United States, STEM education has become a hot topic in the field of basic education reform globally. As the earliest practitioner of the world in STEM education reform, the United States has established a relatively complete development profile for the development of STEM education, with rich development experience accumulated. A review of the path of STEM education in the United States demonstrates that in each stage of STEM education, it is closely associated with specific social and economic development context, driven by certain unique mechanisms. Exploration of the growth pathway of STEM education in the United States from theory to practice would deliver new horizons for the research on STEM education.

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2 Literature Review

CiteSpace information visualization software can detect research hotspots and analyze research progresses in a specific field by measuring the literature in that field and drawing a visual map. This software has proven to be an effective bibliometric tool to summarize the development patterns, identify the classic basic literature and explore the research evolution path for scientific fields.

In order to comprehensively uncover the thematic focuses and development characteristics of STEM education research, this study would, by using CiteSpaceV software, to conduct knowledge map analyses on the journal literature data related to STEM education research collected in the Web of Science core collection databases from 2011 to 2021, so as to get an effective picture about STEM research.

Keywords are the terms that are abstracted by an author to summarize the topic of an article. Since keywords are an author's highly generalized and refined academic thoughts, research topics and research content for a specific study, they can also be used as a way and method for analyzing research topics. In addition, by examining the frequency of occurrence of keywords in a field, it is possible to find the research hotspots in a field and identify the update speed of research content and the vitality of disciplinary research in a field.

In this study, the collected samples' standardized data were imported into the CiteSpace software. The time period was selected from 2011 to 2022. In each time period, TopN = 50 were retained by default. For the analysis item, "keyword" was selected. And the co-occurrence map of keywords related to STEM educational research from 2011 to 2022 was drawn. The size of the nodes in the map is related to the amount of keywords (i.e., the more frequently a keyword appears, the larger its node is). The connections between nodes can reflect the co-occurrence frequency between different keywords. It can be observed that the map so created has a total of N = 578 nodes, E = 5427 connections, and Density = 0.0325 for network density.

In this study, a total of 578 keywords were extracted, and the cumulative total frequency of the keywords reached 15,124 times. The top 50 keywords were summarized based on the literature data in the WOS database, as shown in the following table. The centrality in the table can showcase the importance of a certain keyword in the entire

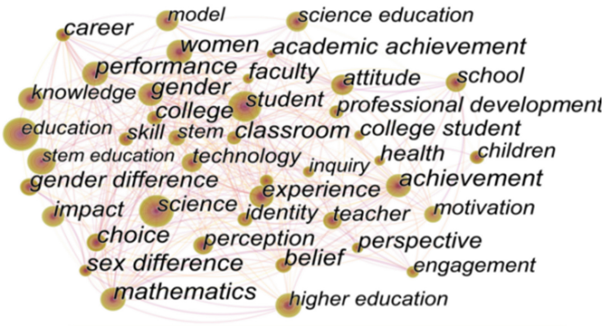

Fig. 1. The co-occurrence map of keywords related to STEM education research

Table 1. List of high-frequency subject terms in STEM education research

No.	Frequency	Centrality	Keyword	No.	Frequency	Centrality	Keyword
1	760	0.01	education	21	148	0.03	perception
2	751	0.01	science	22	135	0.02	teacher
3	501	0.02	student	23	132	0.03	choice
4	396	0.01	stem education	24	126	0.01	identity
5	326	0.01	higher education	25	125	0.02	belief
6	295	0.02	achievement	26	125	0.03	gender difference
7	294	0.03	performance	27	122	0.02	college
8	266	0.01	women	28	120	0.01	self efficacy
9	260	0.02	mathematics	29	103	0.01	engagement
10	257	0.02	gender	30	103	0.03	professional development
11	245	0.02	impact	31	102	0.01	persistence
12	234	0.01	knowledge	31	102	0.01	race
13	216	0.02	experience	33	101	0.04	classroom
14	207	0.01	model	34	99	0.02	design
15	200	0.01	technology	35	95	0.02	career
16	185	0.03	attitude	36	93	0.03	outcm
17	183	0.01	science education	37	90	0	engineering education
18	172	0.02	school	38	88	0.02	participation
19	159	0.01	stem	39	88	0.03	program
20	148	0.01	motivation	40	88	0.03	skill

keyword co-occurrence network, as well as the research hotspots and topics in this field in a certain period of time.

According to Fig. 1 and Table 1 and 2, the following 20 main high-frequency terms and high-centrality keywords can, to some extent, demonstrate the major research hotspots: education, science, student, stem education, higher education, achievement, performance, women, mathematics, gender, impact, knowledge, experience, model, technology, attitude, science education, school, stem, and motivation. Based on the analysis of research hotspots in STEM education, the current researches can be summarized into: (1) Understanding of STEM concepts; (2) Development of STEM research

Table 2. List of key node literature information in STEM education research

No.	Citation Frequency	Year	Author Name	Title
1	79	2016	Kelley TR	A conceptual framework for integrated STEM education
2	74	2014	Freeman S	Active learning increases student performance in science, engineering, and mathematics
3	57	2016	English LD	STEM education K-12: perspectives on integration
4	55	2018	Stains M	Anatomy of STEM teaching inNorth American universities
5	47	2017	Cheryan S	Why are some STEMfields more gender balancedthan others
6	45	2015	Patton MQ	BUNDLE: Patton: Qualitative Research & Evaluation Methods 4e
7	44	2013	Wang XL	Why Students Choose STEM Majors: Motivation, High School Learning, and Postsecondary Context of Support
8	44	2017	Wang MT	Gender Gap in Science, Technology, Engineering, and Mathematics (STEM): Current Knowledge, Implications for Practice, Policy, and Future Directions
9	38	2014	Natl Acad Engn	STEM Integration in K-12 Education: Status, Prospects, and an Agenda for Research
10	37	2019	Margot KC	Teachers' perception of STEM integration and education: a systematic iterature review

methodologies; (3) Optimization of STEM teaching strategies; (4) Research on students' learning effectiveness and academic performance; and (5) STEM and educational equality.

3 The Connotation of STEM Education

As early as in 1986, the National Science Board (NSB) of US published the report of "Undergraduate Science, Mathematics and Engineering Education", also known as the Neal panel's report. It was the first policy guidance document on STEM education in the United States, and also the beginning of the development of STEM education [1].

"STEM" officially appeared as an educational term in 2001, when the National Science Foundation (NSF) of US first adopted the acronym "STEM" to refer to the courses of science, technology, engineering and math, indicating the official emergence of STEM education. The connotation of STEM education has not been restricted to the four disciplines of science, technology, engineering and mathematics since the beginning -- NSF has defined a wide range of STEM fields, which cover not only such common scientific domains as mathematics, natural sciences, engineering, computer and information science, but also such social sciences as psychology, economics, sociology and political science. [2].

In 2015, Professor Carla Johnson of Purdue University began to lead the formulation of the "STEM Road Map", a STEM curriculum plan for primary and secondary school students across the United States, which defines a new concept of STEM education. She pointed out that STEM education can be regarded as a teaching methodplogy, but it should be deemed more as a teaching idea or teaching philosophy. STEM education covers science inquiry, technology and engineering design, mathematical analysis, and 21st-century interdisciplinary themes and skills, and strives to deliver on standards-based teaching of science and mathematics.[3] This definition's cognition of integration exceeds the previous emphases just on content levels by attaching importance to the independent value of different STEM disciplines and the interaction between them, while highlighting the attention to students' integrated thinking process and skills. Therefore, it represents a new level of the integrated conceptualization of STEM.

4 The Development Process of STEM Education from Theory to Practice

Globalization entered a rapid development track in the 1980s. As the main driver of the modern globalization, the United States has, on the one hand, reaped the capital dividends brought about by globalization, and on the other hand, had to bear the hidden risks under globalization, including industrial hollow-out, deficient technical talents for manufacturing industries and other problems. In the context of the contradiction between school education and social talent demand, STEM education is simply the product of such school education reforms. Generally, STEM education has presented the following evolution trajectory from theory to practice (Fig. 2).

4.1 Emergence of the Concept of STEM Education

In 1980s, the global investment and trade system was in its early stage of establishment. In order to cut production costs as much as possible, the American manufacturing industry began to move overseas. With the continuous decline of the proportion of domestic real industries, a large volume of national capital flooded into emerging industries, such as service industry, real estate, finance and insurance. During this period, the tertiary industry dominated by knowledge and information networks boomed, and knowledge-intensive industries emerged. Driven by the growth of knowledge-intensive industries, the entire society of the United States began to focus their attention on popular science education, expecting to improve the national scientific literacy through education

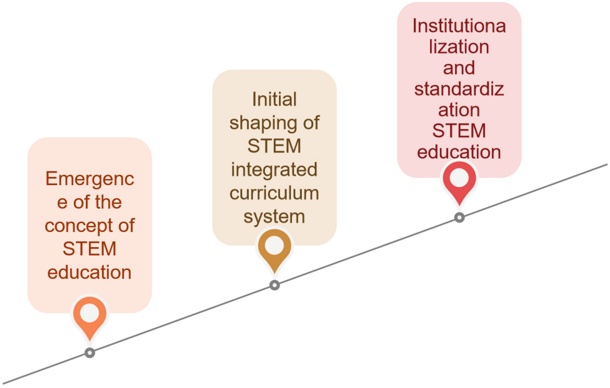

Fig. 2. The development process of STEM education from theory to practice

and hold the leading position of US in the fields of industry, commerce and scientific invention. Under such context, the National Science Board of US issued a report titled "Undergraduate Science, Mathematics and Engineering Education" in 1986, which proposed the phrase of "Science, Mathematics, Engineering and Technology Education" for the first time. This report is also widely regarded as the origin of STEM education in the United States by the academic circles. [4].

It was the main trend of science education reform in the 1980s to realize mutual crossover and interdisciplinary integration between various disciplines in the field of science. In the "2061" program for American education reformation, it is required that the courses for science, mathematics and technology be coordinated by teachers for various subjects in different grades, and the learning schedules developed shall help students understand science, mathematics and technology as well as the relationship between these courses and other human achievements. In this period, people started to explore different disciplines in the scientific field from a holistic view, rather than discipline-wise perspectives, thus laying a foundation for the emergence of STEM education. With the implementation of reforms in popular science education, the concept of STEM education converged into an ideological trend of STEM education. However, a complete STEM education system had yet to be formally established.

4.2 Initial Shaping of STEM Integrated Curriculum System

4.2.1 Social Background

The U.S. industrial structure shifted to highly value-added industries, such as high-end designs and technological services, in the new century as US manufacturing industry continued to move abroad and the domestic virtual economy flourished. However, the shortcomings in its domestic industrial chains got increasingly remarkable, and the resilience and resistance of the US economic development declined due to lack of manufacturing. Therefore, after many years of "deindustrialization", the United States gradually realized that an economy that depends heavily on the tertiary industry has its disadvantages that cannot be ignored. So it began to focus on promoting the development and return of the manufacturing industry and goading this industry to reflow to the United States.

On the one hand, the continuous exodus of the manufacturing industry and the boom of the tertiary industry represented by the financial industry dampened students' interest in learning and selecting the science majors, especially in "hard science" represented by physics and chemistry. This alarmed the insufficient STEM workforce reserves in US. On the other hand, although researchers had fully demonstrated in theory the value and approach of cultivating "scientific literacy" based on constructivism, the path from theoretical blueprint to concrete practice was still in the process of fumbling.

4.2.2 Formation of an Integrated Curriculum System

According to a framework offered by the Partnership for 21st Century Learning (P21) [5], the skills required by the talents in the 21st century are composed of the following three ability modules: learning and innovation skills; media and information technology skills (i.e., information literacy, media literacy, and ICT literacy); and life and vocation skills (including adaptability, autonomy, cross-cultural communication skills, job competency, leadership and sense of responsibility). Under these ability-oriented educational goals, by establishing linkages between science, technology, engineering or mathematics, STEM education can improve the ability of students in comprehensively apply knowledge of various disciplines to solve practical problems. It can achieve problem solving or task delivery through multidisciplinary integration, so the nature of integration is its essential attribute (Fig. 3).

Specifically, as to how to consolidate science, technology, engineering and mathematics to construct integrated STEM curricula, the common answer acquired by researchers is to incorporate them into an engineering design framework, so as to achieve STEM integration by use engineering as the "glue". "STEM curricula should be integrative" has become a consensus among researchers. Based on a pulley system model, Todd R. Kelley et al. have visualized the basic contextual relationship between engineering designs, on the one hand, and the scientific inquiry, technical literacy and mathematical reasoning, on the other hand (as shown in the Fig. 4) [6]. In this system, four sets of

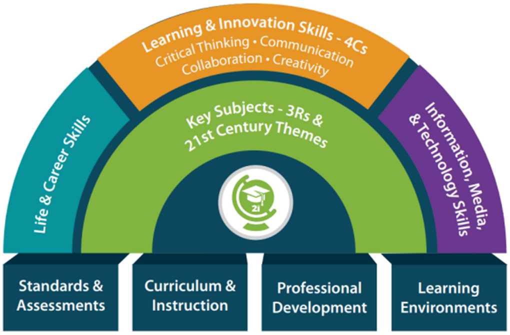

Fig. 3. Framework offered by the Partnership for 21st Century Learning (P21)

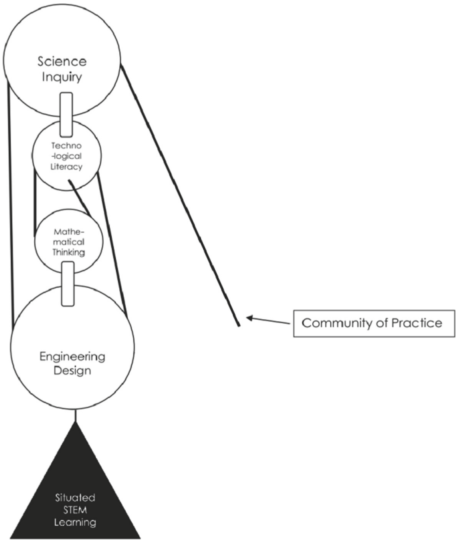

Fig. 4. Graphic of conceptual framework for STEM learning

pulleys connect the heavy object together; in other words, four groups of forces are required to work cooperatively to pull up the heavy object in the easiest manner. When mapped in curriculum design, this integrative attribute is rendered as a curriculum development method centered on themes, rather than on subject knowledge; when mapped in the choice of teaching means, it is presented as a teaching implementation strategy that focuses on students' self-motivated inquiry.

4.3 Institutionalization and Standardization STEM Education

4.3.1 Social Background

In 2006, the subprime mortgage crisis broke out in the United States. Excessive financial innovations and debt-driven growth patterns prompted the US government to correct its previous industrial routes and rethink how to strike a balance between the real and virtual economies. In this context, the U.S. government put forward a "reindustrialization" strategy, trying to revive U.S. economy by revitalizing the domestic manufacturing industry. After Trump took office, he proposed the "America First" strategy to drive the repatriation of the US manufacturing industry, prevent the loss of jobs and enhance the competitiveness of the US economy. However, the key to whether the manufacturing industry can be effectively repatriated lies in whether the domestic relevant labor reserves are sufficient. Reservation of enough STEM talents has even become pivotal to the success of the national reindustrialization strategy. Therefore, since 2007, the federal government has advanced STEM education from a national strategic perspective. This is not only a forward-looking judgment on future talents, but also the bottleneck and key to the successful implementation of its reindustrialization strategy.

4.3.2 Legislation of STEM Education for National Institutionalization

Education legislation is to set forth education policies in the form of laws through legislative procedures, so as to raise the public's awareness of the importance of education policies, establish or reform the existing education systems, and promote the development of education undertakings. As an important form of support for the advancement in STEM education reform, the US federal government has promulgated a series of macro and strategic tactics, such as the National Competition Law of 2007, the National Competition Law Reauthorization Act of 2010, and the STEM Education Act of 2015, among others, which raise STEM education to a strategic position directly linked to the nation's international competitiveness in the form of legal provisions. Such legislation provides an institutional guarantee for the federal government to make macro-promotion of STEM education.

In addition, the Obama Administration had established the Committee on STEM Education to carry out a series of national strategies, purposed to deepen the impact of federal investment on STEM teaching and learning. The Committee promulgated the "Federal Science, Technology, Engineering and Mathematics Education Five-Year Strategic Plan", aimed at facilitating the federal agencies to utilize the federal investment rationally and effectively and prioritize the development of national STEM education.

4.3.3 Standardized STEM Curriculum Construction

Standardized curriculum construction means that at this stage, the development of STEM curricula went beyond scattered and random project experiments, but began to seek a unified action framework to achieve the best benefits of curriculum activities.

In 2007, the federal government's first basic-stage STEM education-related report "National Action Plan" put forward the vision of "building up a nationally unified K-12 consistent STEM education content system" [7], which requires the design of STEM teaching content achieve system connections between different grades, so that students' accumulated knowledge and skills could become the foundation for their success in the next grade when they move from one grade to the next.

Jo Anne Vasquez, former President of the National Science Teachers Association (NSTA), pays focused attention to the research on elements of interdisciplinary integrated STEM classroom in Grades 3–8. By relying on the five guiding principles for STEM instructional design, some interdisciplinary STEM curricula and unit plan templates were developed for direct use or reference by teachers. [8].

In 2013, Professor Carla Johnson at School of Education of Purdue University began to preside over a STEM curriculum development project -- STEM Road Map, and published a monograph on the curriculum system -- "STEM Road Map: A Framework of K-12 Integrated STEM Education". Subsequently, the research team cooperated with NSTA to publish textbooks for 13 grades and each of the core concepts. This indicated that STEM education has evolved from a loose alliance for science, mathematics, engineering and technology to a necessary component of the education system with "curricula" as the carrier, and this also means that STEM education has completed its development from theory to practice.

5 Prospects of the Development Trend of STEM Education

In 2016, based on the development visions and suggestions on STEM in the next ten years as proposed by scholars in a seminar, the U.S. Institute and the U.S. Department of Education jointly released a report titled “STEM2026: A Vision for Innovation in STEM Education”, which described the then-current research on STEM education and explored how to improve STEM teaching and learning; therefore, it has very clear guiding significance for the development of STEM education. This study believes that in the future, the development of STEM education will showcase the following trends:

5.1 Information Technology Will Deepen the STEM Learning

According to the report of “STEM 2026”, six categories of technologies could disrupt STEM classrooms in the future, including: online collaboration tools, online hybrid educational environments, immersive media, simulation games, intelligent tutoring systems, and augmented and virtual reality. These technologies could deepen STEM learning and infinitely expand the spatial reach of physical classrooms.

Flexible and inclusive learning spaces refer to more flexible spaces that are provided to educators and learners in terms of organization, equipment and information retrieval, including traditional classrooms, the natural world, maker spaces, VR- or technology-based platforms, etc., so as to boost learners’ STEM experience. Flexible learning spaces can accommodate all sorts of learning activities, spark students’ creativity, and boost collaborative learning, discovery learning and experimental learning. When transcending time and space constraints, learning spaces can also provide new models for facilitating the exploration of STEM concepts and the development of STEM skills.

In the future, STEM education will create more flexible and inclusive learning spaces by leveraging the tools that can turn over classrooms and provide technology support, while creating effective mechanisms to ensure the fairness in access and use of these methods and tools. The future classrooms will be learner-centered, and learners can acquire knowledge through online videos outside classrooms and then apply the learned content more actively in classrooms. Learners can also acquire interdisciplinary and more authentic STEM learning experience via other technologies.

5.2 Intelligent Measurement Methods for Learning

As indicated by Barack Obama, “the whole nation shall rethink how to use Fewer, Smarter, and Better assessments for students”. [9] The future learning measurement methods will be more innovative and operable, so as to fully reflect the diversification of learners’ abilities. In this way, students can sense the achievements in STEM learning, without feeling much more pressure. The STEM2026 report points out that the future measurement of learning will be operable. Formative evaluations will be adopted that don’t take up too much classroom time but can bring educators the real learning data about learners.

With the introduction of technologies, such approaches as electronic badges, educational games and real-time assessments are all innovative practices of learning measurement. Among them, real-time assessments can identify meaningful patterns of behavior, so as to help educators adjust their instruction based on learning measurements. Organizations like "Ripple Effects" and "The Social Express" provide learners with virtual environments, storytelling platforms and interactive experiences, which are new attempts to measure learners' social abilities [10, 11].

5.3 Learning by Exploring the Unknown and Making Trial-and-Error

A key challenge faced by STEM education in the future is how to design the curricula and learning activities that allow students to try and fail. Trials with setbacks and failures are great opportunities to reinforce learning. The classroom activities that can increase fun and risk would encourage learners to take risks in trying new ways to solve complex issues. It is the new questions proposed after failures that may trigger new investigations and determine why previous innovations have not functioned.

Currently, the vigorous maker-related events are just an important attempt in this regard. Maker-space programs in terms of STEM can hike students' engagement in STEM learning, thus helping promote the process of STEM education. By strengthening students' vocational skills via creating "Maker spaces", the innovative ways can attract students from different cultural backgrounds and cultivate their creativity. In addition, some projects are trying to integrate "maker events" into their curricula or informal after-school programs, so as to support the mergence of "maker events" into classroom teaching.

6 Conclusion

This paper systematically discusses the development of STEM education from theory to practice. In the future, STEM education will require the process of obtaining learning results. And in this process, the learning behavior of learners will be developed and measured; their psychology of fearing failures will be corrected, allowing learners to make mistakes; and the influence of maker events will be deepened by encouraging the use of maker spaces to forge learning activities of local features, so as to redesign classroom activities that can boost fun and risk.

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