RESEARCH ARTICLE

Historical Foundations of STEM/STEAM Technologies in Education: A Semiotic Perspective

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Abstract
STEM technologies have emerged as one of the most widely discussed topics in contemporary educational discourse, valued for their interdisciplinarity, emphasis on innovation, and encouragement of creativity. STEM and its expanded version, STEAM, are increasingly recognized as central to 21st-century educational innovation. This paper analyzes the historical foundations of these approaches through the lens of semiotics—a methodological framework that transcends disciplinary boundaries. By comparing the development of STEM/STEAM with the historical evolution of European educational systems, the study demonstrates that these modern educational models are deeply rooted in philosophical and scientific traditions. Drawing from semiotic and comparative-historical methodologies, the analysis highlights mathematics as a central and historically privileged element, tracing its conceptual origins from ancient philosophy to modern science. The paper concludes with a forward-looking perspective, suggesting the likely incorporation of psychological and social sciences into the STEAM framework, following patterns observed in its historical development.

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1. Introduction

STEM (Science, Technology, Engineering, Mathematics) technologies represent one of the most transformative trends in contemporary education. Their popularity stems from the ability to integrate various disciplines into a cohesive educational framework that fosters creativity, critical thinking, and practical problem-solving (Rafikova, 2022, pp. 852–859). The core principle of STEM education lies in an integrated pedagogical approach that guides students through a structured learning process—from problem formulation to solution implementation and product development (Uspaeva & Gachaev, 2022, pp. 110–114). The more recent addition of the Arts to create STEAM underscores the growing appreciation for creativity and cultural context in technical learning.

This study proposes a semiotic approach to analyzing STEM/STEAM education, focusing on how meaning is constructed through signs and systems of signs. Semiotics—despite being a relatively young field—is increasingly recognized for its capacity to serve as a universal methodology in interdisciplinary research. Each scientific field operates within its own sign system and terminological structure, shaping distinct discourses. Even in mathematics and engineering, where abstraction dominates, the language of representation remains central. Semiotic analysis, complemented by the comparative-historical method, enables us to trace the philosophical and cultural origins of STEM/STEAM and examine their evolving role in shaping modern education.

2. Conceptual Framework: STEM, STEAM, and Sign Systems

A useful entry point into the semiotic analysis of STEM/STEAM is the acronyms themselves. In the English-speaking context, *STEM* encompasses Science, Technology, Engineering, and Mathematics. In the German context, the equivalent acronym *MINT* (Mathematik, Informatik, Naturwissenschaften, Technik) highlights Mathematics, Informatics, Natural Sciences, and Technology—emphasizing natural sciences more explicitly. *STEAM* adds *Art* to the formula, signifying a more holistic view of human creativity alongside scientific inquiry.

Mathematics occupies a central position in all variations of these models. Its foundational role is historically consistent with how knowledge systems have developed in both Western philosophy and science. Mathematics has long been aligned with the natural sciences, particularly physics. In the Russian academic tradition, this is formalized in the combined title "Doctor of Physical and Mathematical Sciences," reflecting their historical and conceptual interconnectedness.

The famous aphorism of Galileo Galilei—*"Il libro della natura è scritto in lingua matematica"* ("The book of nature is written in the language of mathematics")—underscores this deep relationship. Galileo's claim builds on a lineage of thought extending back to ancient natural philosophy. In pre-Socratic Greek philosophy, Pythagoras proposed that the essence (*ousia*) of all things was numerical in nature. As A.F. Losev (1982, pp. 284–285) notes, the Pythagoreans initially did not distinguish numbers from physical objects and later conceptualized numbers as metaphysical entities. This Pythagorean worldview regarded numbers not merely as descriptors but as generative structures underlying all phenomena.

Neoplatonist philosopher Iamblichus, in *On the Pythagorean Life*, reports that Pythagoras often told his students, *"All things are like numbers."* This suggests that early mathematics was not merely analytical or computational, but ontological—it shaped one's understanding of existence. In this sense, the Pythagorean school can be considered one of the earliest educational models that prioritized mathematics as a way of understanding the world holistically.

However, the mathematics of Pythagoras differs substantially from contemporary conceptions. For him, numbers were not abstractions but concrete, existing entities. Mathematics, therefore, did not describe reality—it constituted it. Humanity's task was to discover and comprehend its inherent logic.

3. Semiotics and the Structure of Scientific Discourse

This Pythagorean view parallels a key idea in modern semiotics: that the structure of knowledge is mediated through sign systems. Each academic discipline, whether in the humanities or sciences, functions within its own framework of symbols, language, and discursive norms. Even mathematics, often viewed as an abstract universal, relies on specific symbolic representations and a shared cultural context to be understood and applied.

From this standpoint, educational technologies such as STEM and STEAM are not merely pedagogical innovations—they are semiotic structures that encode complex relationships between disciplines, knowledge traditions, and societal needs. Interdisciplinarity, in this context, becomes not just a pragmatic tool but a semiotic strategy: the linking of multiple sign systems into a coherent and generative educational framework.

4. Historical Evolution and Future Prospects

The integration of artistic disciplines into STEM, resulting in the STEAM framework, reflects an ongoing historical tendency toward broader educational inclusivity. If we follow this trajectory, it is plausible to expect that future iterations of these models will incorporate elements from the psychological and social sciences. This projection mirrors the historical development of education in Europe, where the Enlightenment ideal of rational knowledge gradually gave way to holistic and humanistic educational paradigms.

The interdisciplinary semiotic approach supports this expansion. As each new domain is introduced into the framework, it brings with it a distinct set of signs, symbols, and discursive practices. Understanding how these integrate within a unified educational model is essential for the future of curriculum design and innovation.

This study has argued that modern STEM and STEAM technologies are deeply rooted in the historical and philosophical traditions of European education. Through semiotic and comparative-historical analysis, we have demonstrated that even the most contemporary pedagogical innovations are expressions of longstanding epistemological structures. Mathematics, as both a symbolic and philosophical system, remains central to this discourse. Looking ahead, the integration of psychological, cultural, and social perspectives into STEM/STEAM education appears both necessary and inevitable, further underscoring the utility of semiotic methods in educational theory and practice.

5. Mathematics, Semiotics, and the Human Construction of Knowledge

There is a well-known position in philosophical literature suggesting that Aristotle, to some extent, distances himself from the mathematical worldview, prioritizing qualitative over quantitative approaches to the study of nature. However, upon closer inspection, this distinction may not be as sharp as often assumed. Aristotle refers to scientists as "physicists" (*physiologoi*), though in antiquity this term (*φύσις + λόγος*) signified "discourse about nature," rather than its modern usage referring to the medical or biological sciences. In this conceptual framework, the scientist is positioned as a passive observer, a mirror faithfully reflecting the external cosmos. Thus, despite their methodological differences, both Aristotle and Pythagoras affirm the primacy of nature over human inquiry—the world poses the questions, and the human being responds.

This epistemological stance persists into the scientific revolution. Galileo Galilei's famous dictum—*"The book of nature is written in the language of mathematics"*—implies that the human role is to decipher a prewritten text. Yet simultaneously, Galileo paves the way for a significant shift by advocating for experimentation as a core scientific method. From the 17th century onward, the Aristotelian *physiologos* gives way to the modern natural scientist, who no longer merely receives questions from nature but actively interrogates it through observation, hypothesis, and experimentation.

This transition is poignantly captured by Johann Wolfgang von Goethe, who reinterprets Galileo's aphorism: *"It is often said that numbers rule the world; at the very least, they show how the world is ruled."* Goethe's statement subtly redefines mathematics—not as a cosmic language, but as a structured, human-made system for interpreting reality. Here lies an essential insight: mathematics, as a semiotic system, must be understood in terms of its constructed nature and its limitations.

Mathematics is not a natural language—it is an artificial, secondary sign system. There are no intrinsic "ones" or "twos" in nature; rather, we speak of *one* person or *two* trees. All mathematical signs are human inventions, products of abstraction and cognition. Plato himself acknowledged this when he wrote that numbers "*are only permitted to be thought of, otherwise they cannot be handled*" (*Republic*, Book VII, 526a).

This feature is central to semiotics. As Ferdinand de Saussure, the founder of modern semiology, emphasized, signs possess two defining characteristics: first, they are arbitrary (determined by convention); and second, they are ideal (residing within the realm of mental constructs). The *signifier* (the form of the sign) and the *signified* (its conceptual meaning) both belong to the human psyche and do not correspond directly to material objects. Mathematical signs are no exception; their signification is entirely abstract and mental.

This understanding leads to a provocative conclusion: mathematics, within the STEM/MINT paradigm—which is typically aimed at enhancing natural and technical cognitive competencies—is, paradoxically, a humanitarian discipline. Bertrand Russell once remarked that "*there are only two truly humanistic sciences: pure philosophy and pure mathematics.*" While seemingly counterintuitive, this insight aligns with a semiotic analysis of knowledge systems.

From this perspective, one might even suggest—paradoxically—that mathematics appears "superfluous" within STEM, if one assumes STEM focuses strictly on empirical natural sciences. But this is clearly not the case. Without a mathematical foundation, STEM would lose its internal coherence and methodological rigor. The key lies in understanding that STEM does not merely teach scientific facts; it cultivates forms of reasoning, abstraction, and symbolic cognition.

Plato's views again offer clarity on this point. In *The Republic* (Book VII, 526b–c), he underscores the formative role of mathematics: "*This science is indispensable, since it forces the soul to use pure thinking in pursuit of truth… Even slow learners, if they study it and practice, become more receptive than they were before.*" The term "*mathematics*" (*τα μαθηματα*) in antiquity meant "that which is learned" or "knowable." It was rarely used in isolation; more often it appeared in the phrase *μαθηματικὴ τέχνη*—the mathematical art or technique—indicating that mathematics was always linked with practical application.

This brings us to the second component of STEM: technology. Its inclusion, too, has deep historical roots. In ancient education, the ideal was the *harmonious human being*—skilled equally in the sciences (*musike*) and physical disciplines (*gymnastike*). In this context, re-examining the concept of "technology" is essential.

6. The Philosophical Semantics of Technology

The philosophical implications of technology were profoundly examined by Martin Heidegger in his seminal 1953 essay, *The Question Concerning Technology*. Starting from its conventional instrumental and anthropological definitions, Heidegger argues that technology is more than a tool—it is a mode of *revealing*, a process of bringing forth (*Her-vor-bringen*) something from non-being into presence. In ancient Greece, this process was expressed by the term *ποίησις* (poiesis), a concept that unites creativity, emergence, and truth-seeking.

Plato, in *Phaedrus* (205b), describes *ποίησις* as "*every cause that leads something from non-being into being*." Heidegger interprets this as an ontological transition, wherein technology becomes a pathway through which the concealed (*das Verborgene*) becomes unconcealed (*ἀλήθεια* – truth). He writes: "*A work comes into being only inasmuch as the concealed is revealed. This transition gains momentum in what we call the openness of the concealed. The Greeks had a word for this: ἀλήθεια. The Romans translated it as veritas. We say 'truth', usually meaning the correctness of representation*" (Heidegger, 1953, pp. 221–238).

From this semantic and philosophical standpoint, *technē* is closely linked to *epistēmē*—knowledge. In pre-Platonic and Platonic thought, these terms were nearly synonymous. Heidegger notes that "*both terms refer to knowing in the broadest sense... technē discloses what does not produce itself, what does not yet exist, and thus can be brought forth.*"

In this light, technology is not simply an application of science—it is a creative and epistemological act. It facilitates the emergence of cultural artifacts that did not previously exist. This interpretation provides the philosophical justification for the "T" and "E" components of the STEM model—*technology* and *engineering*—as processes grounded in philosophical inquiry and human creativity.

The Cultural and Philosophical Foundations of STEM/STEAM Education

Turning to engineering, it is useful to revisit the original etymological meaning of the term. The Latin *ingenium* denotes a particular talent or innate gift. Cicero posited that a person has two sources of philosophizing: *doctrina*, referring to externally acquired knowledge through education, and *ingenium*, referring to natural intellectual ability. Giambattista Vico expanded on this, describing *ingenium* as a distinctive form of intelligence more closely aligned with poetic intuition than rational thought. It is *ingenium* that enables the recognition of connections between external forms and internal meanings—an essential creative faculty that fosters non-standard thinking, metaphorical reasoning, and imaginative integration into rational constructs.

As an innate cognitive faculty, *ingenium* is intimately connected with *intelligentia*, a term prominent in medieval philosophy. Thomas Aquinas considered *intelligentia* to be a pure cognitive act, entirely spiritual in nature, representing the realization of *ingenium*. From this perspective, technology, engineering, and mathematics are historically grounded in creative, artistic, and philosophical traditions, rooted in the concepts of *poiesis* in Ancient Greece and *ars* in Rome—terms that emphasize creativity and the artistry of human intellect.

This intellectual lineage is mirrored in the structure of medieval education. The *trivium* and *quadrivium*, foundational to university curricula during the Middle Ages and Renaissance, present a conceptual parallel to the modern evolution from STEM to STEAM educational models. The *trivium*—comprising grammar, rhetoric, and dialectic (logic)—formed the basis of early education. Despite being perceived as "elementary," these disciplines cultivated precise expression and critical thinking. As noted by Gadamer (1988), the ancient Greek term *eu legaine* connoted both eloquence and prudence, reflecting a unity of truth and articulation. "Those who speak well think well" was a guiding principle shared by both philosophers and rhetoricians.

The *quadrivium*, or the "four ways," included arithmetic, geometry, astronomy, and music. These disciplines introduced a natural scientific perspective to education. Notably, music and astronomy were interconnected through Pythagorean concepts of cosmic harmony, underscoring the unity between scientific inquiry and aesthetic order. While *quadrivium* receded temporarily under the influence of early Christian education, the *trivium* persisted and shaped university education well into the High Middle Ages.

Over time, universities evolved from monastic and cathedral schools into institutions of secular learning, with faculties dedicated to theology, law, and liberal arts. The *quadrivium* eventually reemerged as a full university course. The structural expansion of education to include a broader intellectual spectrum anticipated today's integration of the arts into technical education—a movement from STEM (Science, Technology, Engineering, Mathematics) to STEAM (adding the Arts).

This transition reflects a deeper recognition that creativity is indispensable across disciplines. The inclusion of the arts fosters a holistic, integrated learning model that resonates with ancient ideals of harmony, balance, and aesthetic insight. In fact, incorporating creative methods into the study of natural and technical sciences enables more profound and comprehensive educational outcomes.

The philosophical foundation of modern educational technologies lies in this historical continuity. The emergence of STEAM reflects a return to and renewal of enduring educational principles. Furthermore, extrapolating from historical patterns, it is plausible that future educational models will further integrate psychological and social sciences into the STEAM framework—mirroring the trajectory of knowledge expansion during the Enlightenment, when sociology and psychology gained scientific legitimacy.

Such interdisciplinary enrichment will enhance the creative and intellectual development of learners in all fields—whether in engineering, biology, or physics. As in the natural sciences, where phylogeny recapitulates ontogeny, educational systems seem to mirror the stages of their own historical evolution. Education, in this light, is not a static repository of knowledge but a living, dynamic process. The Latin *processus*—meaning both "to move forward" and "to grow"—captures this essence. Like a plant growing from a seed, education unfolds, revealing latent truths (*aletheia*), and developing organically through time.

The purpose of educational technologies is not merely to transfer knowledge or ignite interest, as Plutarch famously asserted, but to *cultivate*—a term rooted in the Latin *colere*. STEM and STEAM methodologies, therefore, should be seen as instruments of cultivation, nurturing the intellectual, moral, and creative growth of learners.

7. Conclusion

The development of STEM and STEAM educational technologies is not an isolated modern phenomenon but a continuation of historical educational paradigms deeply rooted in antiquity and the middle Ages. Through semiotic and philosophical analysis, this paper has shown that the structural evolution of these models parallels the intellectual history of European education—from Pythagoras and Aristotle to Cicero, Aquinas, and Heidegger.

The move toward including the arts—and potentially psychology and social sciences—into STEM is a natural and historically coherent development. As in biological evolution, educational systems undergo a form of "ontogenetic recapitulation," echoing earlier stages in their modern forms. Education, as a *processus*, is a living, growing system—akin to a plant shoot reaching for light. As such, the purpose of educational technology is not to merely transmit knowledge but to *cultivate* human potential. In this sense, STEM/STEAM technologies do not just educate; they *cultivate culture* itself.

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Conflict of Interest

The author declares no conflict of interest related to the publication of this article.

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