An Interdisciplinary View of Education in the Formal and Natural Sciences

From STEM to STREAM to ...

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ABSTRACT

STEM is increasingly a focus for education, from primary school through post-secondary (university) level. It is increasingly recognized and critically important, academically, economically, socially, and politically. At the pre-collegiate level, programs have responded to recommendations for the inclusion of the arts and consideration of medicine and the health sciences, yielding STEAM, or in parochial or religiously affiliated schools, STREAM. However, engaging in this STEM, STEAM, STREAM construct can be complicated and costly in classic business, industry and academic structures. It requires key personnel willing to collaborate, fuzzy collaboration structures which can be hard to granularize in the classical silos, and often a vision of understanding how to coordinate and integrate multiple views on a project. In this article, we consider other complementary disciplines and perspectives, including interdisciplinarity and diversity. While some affect primary and secondary education, our main emphasis is on post-secondary undergraduate education in the STEM disciplines, and on approaches to address those concerns within the constraints of a typical major in the STEM disciplines, and also on implications for team structures in STEM enterprises and research.

1. INTRODUCTION

The world has become ever more reliant on science and technology, and on the mathematics supporting them. They impinge on almost every aspect of life, both directly, and through the engineering and data science driving and direction large-scale research and commercial applications. Over the past 45 years, nations and leaders around the world have created national and regional initiatives to improve, enlarge, or broaden STEM education, the STEM workforce, STEM-based careers and research, and STEM-driven commerce.

The STEM disciplines are not only of intellectual interest in their own right, but ideally act as a consumer of problems and producer of solutions. They also serve as a fruitful source of analogies and transformative approaches in other disciplines. Further, they can themselves create or exacerbate problems, especially if used improperly or carelessly. As a result, STEM needs to be understood in a broader educational and social context.

For precision, note that while Science, Engineering, and Mathematics are well defined (with Mathematics including statistics), Technology covers not only all aspects of Computer Science, artificial intelligence, and software development, but also Information Science, and other uses and applications of computing.

Also, following increasingly common practice, we will use “the formal sciences” to encompass mathematics, statistics, and computing, and sometimes theoretical physics, and “the natural sciences” for biology, chemistry, and physics on the whole. More particularly, “physical sciences” usually means chemistry, physics, and perhaps biochemistry, and “life sciences” covers biology together with the health sciences. Ecology, the earth sciences, environmental science, and sustainability overlap both of these, and we will consider the applied health and environmental sciences separately.

Finally, while data science could be considered part of STEM, relying on all of these fields and others, but on Mathematics and Technology in particular, it is arguably a separate integrated discipline, and we will treat as such below.

This paper addresses concerns about the balance of trying to address the various confusions about STEM education and the importance of ensuring these issues are addressed. The paper will initially look at this issue from the academic perspective and the address industry-specific issues in the later sections. An integrated approach has already begun, with some success, in pre-university education, starting with STEM and working outwards. In Section 2, we briefly overview this effort.

Section 3 then addresses successes in looking at problems through an interdisciplinary lens, within STEM and again incorporating other disciplines and concerns. We consider the ways in which knowledge of and experience with these interactions can enrich the education, careers, and roles of STEM students and professionals. In Section 4, we then focus on these complementary perspectives, using the pre-collegiate STEM efforts as one focus, and identified weaknesses in the preparation of STEM professionals as another, and at the end of the section, look briefly at approaches for integrating some or all of these perspectives in the education of STEM professionals. Section 5 then looks at examples of disciplinary interaction and the need for a broad knowledge base in two areas. Finally, Section 6 concludes with conclusions, future work, and a view on the future of STEM and STEM education. While our focus sometimes concentrates on the formal sciences—mathematics, logic, computer science, and data science—the broad outline is appropriate for all of STEM.

2. STEM INTEGRATION IN PRIMARY AND SECONDARY EDUCATION

In the past 25 years or so, there has been an emphasis in the United States and elsewhere on an integrated approach to STEM in primary education (grades 1-5) [29, 128]. A typical STEM program may entail not only instructor presentation of facts (and hopefully, concepts), but hands-on experience, group learning, and individual or group posters or presentations, often accompanied by field trips and peer interaction/mentoring by students in higher grades.

It has multiple purposes. One obvious purpose is to interest children in STEM study and possible careers, and to provide a better understanding of STEM thinking and processes than previous approaches to elementary-school science education. But it also helps to educate more well-rounded and better-informed future citizens, and to give students a fuller understanding of the applications of STEM and its interactions with society. This approach has also extended to programs in the intermediate grades (some subset of grades 5-9) and secondary education (grades 9-12), although the latter is more often still siloed into separate courses including mathematics, computers, biology, chemistry, and physics, with minimal attempts at interaction.

The concern for an integrated approach, coupled with a desire not to have STEM overshadow the rest of the curriculum, has led to programs that integrate the arts (STEAM) [55, 93], reading and writing (STREAM, which we will label as STREAM-1) [91, 113], and the humanities [SHTREAM] [82]. In religious, particularly Catholic, schools, religion has been integrated—a second interpretation for STREAM, which we will refer to as STREAM-2 [16, 46]. In addition, many programs include a focus on the environment, ecology, earth sciences, and sustainability [22, 45], or on connections to medicine and the health sciences [104], sometimes collectively denoted as STEAMM. Finally, all variants of STEM instruction, both in content and in pedagogy, are (in principle) aware of social and interpersonal issues, diversity, and often security [39, 118].

At their best, these programs can communicate STEM while developing other skills, showing interactions of science and art, using science assignments to strengthen communication skills, addressing ethical issues, and introducing fundamental questions of the nature of science, mathematics, knowledge, and learning. At the worst, of course, these integrated programs use the inclusion of other disciplines to water down the coverage of STEM, using STEM as little more than a backdrop for business as usual.

In fact, a review of the best of these programs may be in order for insights on how to best integrate the arts, social concerns, and consideration of applications into STEM majors. In the next section, we look at some interactions of STEM and other disciplines, and in the following section, at these and other perspectives and their relation to a well-rounded STEM education.

3. AN INTERDISCIPLINARY FOCUS ON STEM ACHIEVEMENTS AND MODERN STEM CULTURE

The STEM disciplines themselves have made enormous progress, creating new knowledge, applications, and social and economic benefits, often through a combination of STEM and other disciplines. Knowledge, practices, and views overlap and can be shared, and knowledge or insights developed in one area can influence others. As one notable recent example, agility has spread as both a meme and a set of guidelines, processes and techniques, from software development into management and production across multiple sectors, also influencing education in multiple disciplines. Data science in particular is full of these examples. For example, we see data collection and AI techniques in everything from our ATMs and GPS systems through amusement parks and smart home devices to our medical experiences. These techniques are growing at an expansive rate, not just for data-driven commerce, research and decision making, but with the adoption of Internet of Things (IoT) models across many areas.

Clearly, STEM disciplines and their mutual and external interactions are a source of solutions, with that interaction resulting in an overall improved standard of living, better health, and a robust economy. But as STEM adds value, it can also raise or worsen problems. One problem is the failure to adequately consider side effects or risks. A second is the economic and opportunity losses—some may result from taking reasonable risks, but too often these come from poor planning or shoddy execution.

Additional problems arise from not considering, or in many cases, not understanding social and ethical issues, such as loss of privacy, increasing social and economic inequality, pollution and climate change, and new kinds of crimes and improper professional behavior. In the health sciences, for example, the increasing use of remote or robotic surgery, and the computerization of nursing stations, can result in decreased personal contact for patients and practitioners, with a possible concomitant loss of practitioner motivation or morale. Medical office automation, without consideration of its social effects or need for training, may displace qualified office personnel, or alternatively, lead to mistakes with possibly serious consequences.

One of the reasons for the inclusion in primary education of religion in STREAM-2 is to allow discussion of such ethical and social responsibilities in early STEM education, with an age-appropriate presentation and focus. This may also be achievable through inclusion of the humanities in SHTREAM, if humanities are understood to touch on philosophy and social science. In either case, it will also be desirable to include some understanding (again, at an appropriate level) of the processes of learning, knowing, and understanding, and of different modes of learning, again touching on philosophy and the social sciences, as well as cognitive science.

Another aspect of pre-collegiate STEM education is group learning and frequently group projects. This corresponds to trends in university education, academic research, and business and industry. Most science is now very much a group or team effort. Quality science, especially dealing with large or complex applications that have social or personal consequences, is arguably best performed by a team with a diversity of backgrounds and a variety of perspectives. These perspectives not only provide contrasting yet often complementary scientific and technological knowledge and insights, backgrounds, but also diverse views on social impacts, ethical issues, security, privacy, economics, stakeholder interests, and more.

In addition, teams, whether involved in scientific research and development, software engineering and DevOps, the health sciences, sustainability and the environment, public policy, or data science, will benefit from strong soft skills, improving teamwork and team structure, and acquiring information and communicating results in an accurate, informative, useful, and persuasive manner. One of our colleagues observes that too many of the data science candidates he interviews or vets seem to have a narrow focus on one area, be it mathematics and/or statistics, computing and software development, graphic design and visualization, data science applications, or business analytics and/or management—and few of these narrowly focused candidates, without some understanding of the other areas, are good candidates for a data science team working on innovative or high-value projects [23].

Overall, there are also obvious implications in post-secondary education. First, an integrated view will result in STEM students taking their general education more seriously, and possibly vice-versa, with non-STEM students seeing the relevance of STEM education to their own careers and intellectual interests. Second, many natural science majors (and a few in the formal sciences) will pursue careers in the health professions or in sustainability and environmental science; conversely, many in the formal sciences (and again, some in the natural sciences) will need to consider aesthetics in order to pursue careers in design, or in developing textbooks and other course material, or will need to consider aesthetics as part of their development projects—from user interfaces to web pages and beyond. Third, law and politics can benefit from technical experts with some prior knowledge of business, law, and the social sciences. Finally, for those entering STEM careers, a broader background will be important in assessing the implications of one's professional work—particularly in sensitive areas such as involvement in military research and development, new drugs and therapies, massive engineering projects, invasive software applications—and in the management of technical projects.

As a result, we consider a number of facets below. First, clearly, we consider STEM and its extensions to the health and environmental sciences, and additional facets of computing. From the arts component of STEAM (and the humanities and reading/writing in SHTREAM) come communication and the arts, and more generally, soft skills and intellectual context. Next, parallel to the religion in STREAM-2, philosophy and ethics (which brings with it a more serious look at logic). Consideration of social issues suggests inclusion of the social sciences, which are already a part of many general education requirements, and preparation for careers, a look at business processes and management perspectives. Finally, we look at interdisciplinary perspectives, and at two already interdisciplinary areas related to STEM, data science and cognitive science.

4. PERSPECTIVES AND CONSIDERATIONS

Across STEM disciplines, common themes persist: value formation (both economic and disciplinary), team development, solid communication skills, analysis of requirements and risks, problem solving and critical thinking, considerations of aesthetics and style, and concern for environmental, social, and ethical issues and impacts.

Taking all of these into account—the integrated perspective on STEM, the interdisciplinary nature of much recent progress in STEM, and the persistence of common themes, we can now survey perspectives that are desirable for a fully-rounded education in STEM, and may be needed by a good interdisciplinary team in STEM or in data science. While this overview in places emphasizes software development and data science, most or all of these will prove useful throughout the STEM universe—although distinctions have been noted. Some topics, such as privacy, will come up repeatedly, but each new discipline offers different insights on those issues.

4.1 STEM and its variants

STEM. The heart of STEM activity will of course be in STEM. All STEM and data science graduates and professionals will require exposure to mathematics, statistics, computing, and science, in varying mixes. For the natural and life sciences, this will include laboratory skills, but these will vary to some extent by discipline; the mathematics, statistics, and computing should ideally not be just that needed for their undergraduate education, but concepts needed in further education and professional life, plus some focus on modeling and design of experiments, to support working with interdisciplinary projects, teams, and academic programs.

In the formal sciences, this will involve rather more mathematics, statistics, and modeling, together with an understanding of the fundamentals of computers and computing, plus programming and software engineering. Again, and conversely, this should ideally include enough exposure to the physical and biological sciences to support communication and development in interdisciplinary academic programs or scientific and related applications.

The common themes mentioned above must also be integrated into STEM education, beginning with STEM courses as such. Two career-oriented but more generally applicable issues that arise in software engineering deserve special mention. The first is consideration of requirements and risk, and the second, the need to maintain communication with stakeholders, which in software engineering largely means the client/customer (a focus of agile methods), management (the focus of DevOps), and team members and other collaborators on the current project.

STEAMM and further extensions of STEM. Transitioning to STEAMM, by inclusion, at least at a conceptual level, of medicine and health professions, and of earth and environmental sciences, ecology, and sustainability, on the one hand, and communication (speaking, listening, reading, writing, presenting, and critiquing) and the arts (the visual arts, music, dance, theater, film, and others) on the other, has been a recent focus of primary, and to a lesser extent, secondary education in STEM. At university level, there are clear benefits in increasing interest in both STEM and non-STEM students, and in improving presentation skills [70].

Further extensions, especially for students in the formal sciences, should extend coverage of technology beyond the computer and computing, programming, and software development, and an introduction to "computational thinking". Extensions should include a fuller understanding of software engineering, on the one hand, and information technology and modern computing and communications infrastructure, on the other, looking at hardware and software architectures. Important aspects of software engineering, beyond development of simple applications, include considerations of stakeholder interests, requirements, and risk, and perhaps some idea of agility and the need for flexible and dynamic problem solving. Even as agile processes make requirements more flexible, increasing interconnectivity makes requirements analysis more demanding [121]. Understanding of the computer can extend from some of the developments in modern computer architectures [49, 79] to the cloud, web and mobile platforms, and the Internet of Things. Moreover, robotics, artificial intelligence, and the Internet of Things are having great effects not only in computing and technology, but on the practice of science, on engineering and medicine, and in data science, as well as raising important philosophical, ethical, safety, and other issues.

Science education also should touch on modern perspectives: in biology, the implications of genetics combined with bioinformatics and tools such as CRISPr [127]; in chemistry, the evolution of organic chemistry toward biochemistry [42]; in physics, at least an overview of modern physics—relativity and quantum theory [33, 122]; and in engineering, to the extent it is covered, the revolution based on computer tools and analyses. There is also much recent discussion on how to do statistics and how to interpret and use its results [7, 18, 58, 90, 108].

4.2 Data Science and the STEM Framework

Beyond these, almost all fields of education now interact with data science—mathematics as a tool, and statistics, science, technology, and engineering both as tools and as clients. Data science in turn relies for accessibility, understandability, and appeal, and sometimes the interpretation of its results, on both the graphic arts and cognitive science. Finally, issues of security, privacy, confidentiality, and intellectual property, as well as safety, affect all of STEM, as well as business, social science, and most other knowledge-based domains.

Data science. While data science is mentioned throughout this document, there are two reasons with STEM students and STEM professionals should have exposure to and knowledge of data science [30, 65, 89]. First, almost all scientific research, other than in formal theory, is likely in the future to involve data science [78]. Second, STEM students and professionals are likely to need or to benefit from key ideas in data science, data analytics, and data visualization. These include: diverse methods of data acquisition, data cleaning to provide high quality, well-structured, and consistent data, the use of data analysis and data mining to find and assess patterns, relationships and linkages, and effective and memorable communication of knowledge and results.

Cognitive science. At the intersection of philosophy, biology, psychology, linguistics, data visualization, and computer science—especially virtual reality and artificial intelligence—is the study of how we develop, think, understand, learn, communicate, teach, empathize, create, and more. Cognitive science [6, 102, 112] and psychology, in combination with mathematical and statistical models, provide important insights and structures for teaching, learning, and childhood and educational development. While it may be too much to expect most undergraduate programs to reach the point where cognitive science can actually be studied in depth, students should become aware of its existence, its interdisciplinary nature and fundamental questions, and its relevance for their studies and careers.

Security, privacy, and safety. All of STEM, except perhaps for the theoretical aspects of the formal sciences, must be concerned with issues of security, privacy, confidentiality, and intellectual property—not just cybersecurity [83, 118] and application flaws [54], but physical security of grounds and devices, and human factors (social engineering [44, 119]) as well, and the complications of distribution and collaboration [8, 75]. Thus security in itself will benefit from an interdisciplinary and systems perspective [62]. Safety is obviously a concern in medicine, environmental science, scientific experimentation, engineering and space science, and development of active systems in robotics and the Internet of Things [10, 13, 34, 47, 66, 87, 129]. These issues not only affect the clients and consumers of STEM: businesses, social organizations, and consumers, but also, not surprisingly, raise substantial ethical concerns.

Security issues are important even in the theoretical aspects of mathematics, computer science, and modern physics, since those disciplines are and will continue to be responsible for many of the cryptographic improvements in cybersecurity [12, 15, 59, 88], as well as for program analyses and models for security and access control [24, 61]. In particular, the potential impact of quantum computing on cybersecurity, affecting all digital and many other security and privacy guarantees [12, 105], provides still another reason for introducing physics to students in computing, and vice-versa.

More on communication, the arts, and the humanities. The integration of the arts into STEM education supports the integration of computing into arts instruction, including electronic music, computer graphics, and the graphic arts. It likewise introduces considerations of aesthetics and style into computer graphics, data visualization, and STEM presentations. The theater arts also contribute to communication skills, including academic and research presentations, and studies in communication—the reading, writing, listening and presenting aspects of STREAM-1—can only aid in further education and careers [70].

There are two other important benefits. The first is tailoring one's writing and presentation to different audiences—one's own team, students, professors, colleagues, management or the business community, or the public. The second, to which STEM education most often contributes, is the need to design one's artifacts to be forward looking, capable of revision, versioning, or dealing with future plans.

In addition, there are the humanities, already present in most general education requirements. Returning to SHTREAM, courses in the humanities can be leveraged to consider additional aspects of aesthetics and style, to address interculturalism and internationalization (compare [76]), and to introduce the digital humanities as a computing and data science domain. One interesting example of the interplay is the use of data science and a technique inspired by genetic reconstruction in deciphering of ancient papyri [125, 126].

4.3 A Broader Academic and Professional Perspective

Philosophy, Ethics, and Logic. There is a great deal of value in philosophy for STEM students and practitioners. Major areas of interest include logic, epistemology, ethics, and the philosophical aspects of cognitive science. Almost all STEM students see some logic in mathematics or computer science courses, but there is significant benefit in seeing logic, including mathematical logic, in isolation. Exposure to its extensions in temporal logic, modal logic, and non-monotonic, statistical, and fuzzy reasoning can also have value in formulating rational arguments, protocols, or understanding of behavior [71].

Epistemology—issues of how we perceive, learn, understand, know, and judge—in addition to being at the core of the philosophy of science [98], is again relevant for cognitive science and, for example, applications in artificial intelligence and data science, and for physical, occupational, and cognitive therapy. (The philosophy of mathematics [38] is a different beast, dealing not so much with the practice of mathematics as the nature of mathematical objects, and more closely related to ontology. But it too is relevant to cognitive science and artificial intelligence, through the Church-Turing Thesis [26]—that human reasoning, or at least mathematical reasoning, can in principle be performed by a computer with unbounded resources.)

A strongly related topic is the limits to knowledge and "paradoxes". Examples in mathematics and computing include Russell's Paradox (there is no set of all sets) and other non-existence results: Gödel's Incompleteness Theorems, and Turing's Undecidability Theorem [71]; in physics, Heisenberg's Uncertainty Principle [33] and the invariance of the speed of light [122]; and in political science and mathematical economics, Arrow's Impossibility Theorem [11, 96]. Understanding that there are inaccessible barriers to knowledge, and that these may have practical ramifications [28], is an important realization.

And finally, recalling STREAM-2, and SHTREAM in its emphasis on humanities, there is a need for a serious study of ethics. While professional ethics and codes of conduct drafted by professional societies for scientific disciplines and health professions suffice for most purposes, at times an understanding of their underlying principles, and of basic ethical principles and dilemmas, will be helpful and perhaps critical [130]. Ethics clearly impacts the conduct of research [81]. It also must be considered, in the formal sciences, in the use of artificial intelligence and robotics [19, 106], privacy in software engineering (leading to the new field of privacy engineering [43]), and multiple aspects of data science and business analytics [110]. In the natural sciences, ethical issues arise in consideration of the environment, dangerous experiments, pharmacology, and elsewhere [40]. And ethical issues pervade the health sciences: privacy, security, data integrity, informed consent, professional conduct, and issues of the rights of women, minorities, children, the dying, and more (with well over 20 journals found by searching for "ethics and medicine"). Biomedical ethics is now a required course in medical schools and in most pre-med programs, dealing with social as well as strictly medical issues [14, 27]. In addition, ethics also overlaps (at least in principle) with the law governing interactions of human beings and institutions.

Social sciences and economics. The social sciences have some significance for STEM education and careers. Psychology—roughly, the behavior of individuals, sociology—the behavior of groups and institutions, anthropology—the behavior of cultures, and political science—the behavior of governments, as well as economics as a social science—the interactions of individuals, labor, capital, and knowledge, are clearly relevant to the practice of STEM. More than that, the understanding of these behaviors and interactions can be crucial in the health sciences, software engineering, and data science, in particular, and conversely, these fields and the rest of STEM can supply information and insights for those social sciences. Human factors, both in terms of social engineering [44, 119] and the motivations of attackers, are also important for security and privacy, including cybersecurity.

In addition, the interactions of enterprises and of teams occur within the social and intellectual universe, parts of which are best understood through the social sciences. These also are important for documenting and understanding changes in social norms and expectations, and in interpreting the motivations and behaviors of individuals, groups and institutions. Social/cultural norms and political processes also affect research, development, and deployment. Finally, civic responsibility as an educated STEM professional will benefit from an understanding of these behaviors and motivations.

The social sciences, interacting with the health sciences and cognitive science, also provide an opportunity to deal with physical, neurological, cognitive, and other differences. Understanding these differences can be important not only in careers touching on the social or health sciences, but also, for example, in formulating and addressing accessibility requirements in software engineering.

4.4 Business and STEM

Business process and management perspectives. Many STEM graduates will eventually assume management, leadership, or consulting responsibilities, whether in academia, software development, applied research and development, the health sciences, or other areas—and most of the rest will be constrained by economic realities, and have to interact with managers, managers and other business specialists.

Thus, a good STEM education should incorporate some understanding of management and the business view of economics, and probably a bit of marketing as well—an understanding that is certainly helpful in understanding the DevOps perspective [99, 109]. Likewise, STEM students should attain an understanding of the nature, processes, benefits and costs of law, standards, and codes of professional conduct, especially as applies to STEM research, careers, and enterprises.

In addition, studying business processes brings up three overlapping and pervasive areas in the intersection between business and STEM. The first is social media and e-business presence, with social media both a key source of both information and a target for marketing, and e-business an increasingly important and in some sectors dominant source of both customer contact and revenue. The second is business analytics [77], using data collection (often from social media and e-business), data science, statistics, and artificial intelligence to extract business information. Finally, decision science uses the results of business analytics plus additional mathematical and statistical models to support decision making, planning, personnel management, marketing and advertising, and other business processes. (Business analytics play such an important role that decision science is sometimes now identified with it [1].)

These areas also form a key part of requirements and risk analysis and management, which are key initial and ongoing aspects of most ventures, whether a scientific experiment, a software development project, development of a new drug or cosmetic, or forming a new startup company. Along with physical risks, and security and privacy concerns as discussed above, management, marketing, economic, and legal concerns need to be identified and addressed (where, for example, marketing for an academic research project may mean its appeal to the broader research community, its ability to attract students, or the possibility for additional research in the same area or on similar questions).

Finally, at the intersection of technology and business, there is agility. To understand modern software development, one must be at least aware of the agile revolution, beginning with the Agile Manifesto [2], and founded on earlier codifications of object-oriented software development and design and other patterns, and structured, tool-supported configuration and change management [36, 56, 57, 63, 72, 92], with the themes of customer satisfaction and communication, continuous delivery of usable products, and rapid, efficient, and effective response to change. Even development efforts that explicitly use a different methodology will be influenced by some of the guidelines and practices that characterize agile development.

In corporate practice, agile software development has been extended and complemented by DevOps, driven by continuous integration of development and deployment, with management satisfaction and communication and interaction with IT operations paralleling agile's emphasis on the customer [99, 109]. Wth the realization that security has to be addressed continually and from the start, the combination has evolved further into DevSecOps [67, 84], and the Agile/DevOps/SecDevOps approach is being adapted in varying degrees for engineering, management, scientific development beyond basic research, and business processes [53, 80, 111, 120].

4.5 Professional Competencies, Interdisciplinarity, and Diversity

Soft Skills and Intellectual Context. There is now an increasing awareness that long-term success in STEM careers is correlated with high-quality soft skills—it is not impossible but much more difficult to succeed without them [20, 35, 100]. Of prime importance among these skills are communication, critical thinking and problem solving, teamwork and leadership, lifelong learning, and interpersonal skills [31, 37, 68, 73] (also compare [9, 121]).

Communication notably includes not just the important ability to express oneself in speech and in writing—clearly, precisely, informatively, constructively, and persuasively, as the occasion warrants, but also the equally important abilities of reading and abstracting content, and of listening and interacting.

Critical thinking and problem solving seem to be fairly well understood in STEM contexts, but more attention to problem understanding—we have already mentioned modeling, design of experiments or software applications, and requirements and risk analysis. But there is more: novel problems require creative and often integrative solutions—finding just the right analogs, often from very different fields or applications, and combining them with new insights.

Elegant modeling and design in software engineering can make an application or its interfaces more understandable, learnable, and usable. Further, as has been seen with patterns and refactoring in software engineering, elegance and clean design can support modifiability, extension, and reuse. While such approaches may seem interfere with performance, efficiency and performance can typically be recovered by post-design, largely automated optimization and tuning.

Similarly, clean, elegant mathematical exposition and proof, and designs of scientific and statistical experiments most often support generalization or adaptation for other purposes. One key principle appears to be orthogonality—identifying and where possible separating the handling of weakly overlapping or differently motivated concerns.

Teamwork entails not only working as a member of a team, but supporting the team, being willing to differ, to constructively critique, and even to warn where needed, and taking (formal or informal) leadership when one has the expertise or other relevant capabilities, while following interactively at other times. Understanding the practices of pedagogy, interactive learning, research, and presentation in one's own discipline is also of great value in explaining, learning, teaching, and to some extent team formation, in both internal and external contexts.

While we have already mentioned economics and cognitive science, exposure to the other social sciences will also be beneficial: psychology, which describes and analyzes individual and small group dynamics; sociology, which does the same for larger groups and institutions; and political science and government, which is involved with international relations, government institutions and those that interact with it, and the making and enforcement of laws.

Interdisciplinarity and Diversity. Finally, it has become clear that teams working on STEM projects in academia or in the real world often benefit from diversity—of viewpoints, approaches, disciplinary background, and social factors and demographics [21]. Ideally, students should be exposed to teamwork with varying groups and to interdisciplinary courses, to acquire intellectual breadth, to develop social and professional maturity, and as preparation for the very real possibility of becoming a member of a diverse research group or a software development or data science team, and/or of working on an interdisciplinary problem [39, 48, 86, 97]. Another interdisciplinary activity is digital transformation, which requires a team with a mix of business, STEM, data science, and soft skills [9].

Diversity is particularly important in requirements and risk analysis, and in model and experiment design [3, 4]. Two notable situations both benefit from social/demographic diversity, and deal with identifying and differentiating stakeholders and their interests or interactions: the need to include women and minorities in medical and related experiments, and creating marketing strategies for new applications or products. In the first case, not having done so led to ignoring or misidentifying effects and risks of drugs, treatments, or therapies [40]. In the second, lacking diversity led to product failures and a good deal of wasted time, effort, and money.

An exposure to cybernetics and systemics, especially second-order cybernetics [SOC], can complement this approach (see for example [52, 103, 115, 116]). The first-order cybernetic study of complex, reflexive, and possibly non-linear systems can provide an understanding of (mechanical, electronic, and computer-driven) systems governed by protocols or interacting processes, and a broader view of problem solving in engineering and in wider domains for non-engineering STEM students and professionals. Second-order cybernetics then adds the interaction of observer and observed, more in the sense of social science than of quantum physics, and adds reflectivity—thought and process evolution—to first-order reflexivity—feedback loops and control mechanisms. Community and team interactions can also be considered from the SOC perspective [37].

4.6 Implementation into Curriculum

Once the desirable components and complements of a superb STEM education, resting on a solid baccalaureate level foundation in one's own discipline, have been identified, we can ask: To what extent is such an education feasible? How can it be brought about? And what stands in the way?

Four possible routes suggest themselves: an interdisciplinary bachelor's degree, a focused bachelor's degree with a general education component chosen to enhance the degree, an interdisciplinary graduate degree, or a post-baccalaureate credential such as a certificate or a module in a micro-curriculum framework.

Each has its advantages and difficulties. The first two baccalaureate alternatives will of course be quicker and most likely less expensive, and can address all of these perspectives over a four-year timeframe. However, the first alternative, an interdisciplinary baccalaureate major, would require either formation of a new program, and probably new department, competing for faculty and students with existing disciplinary programs. The second has the advantage of complementing a full STEM major program, while selecting appropriate general education courses, but runs into at least three problems.

The graduate alternatives offer different tradeoffs. The third approach, an interdisciplinary graduate degree, could either have a content or problem focus, or be fully interdisciplinary. The advantage is that students will have had a full undergraduate degree—athough this may preclude or offer obstacles to those without a suitable STEM undergraduate program—and may also allow students to be employed in career-relevant positions while seeking their degree. The fourth and final approach, a post-graduate credential such as a certificate, of perhaps 3-6 graduate courses, arguably cannot by itself completely solve the problem, but has the possibility of leveraging a student's prior education—and with luck a diverse cohort of students, and planting the seeds of a good interdisciplinary perspective, without the need to cover the full scope of a graduate-level academic discipline. The certificate could, either as a structure or as an option, be coupled with a graduate subject degree, or serve as a stand-alone credential.

Each of these alternatives relies on a substantial institutional commitment and investment, and change in institutional perspectives, policies, and processes. Except to some extent for the second, they are impractical for an individual to otherwise pursue. In most cases, this will mean faculty will need to commit to change (to varying extents) their approach to teaching, and to commit to more involvement in advising and interacting with students. This can be risky for non-tenurable faculty unless the program is well-established, and for probationary faculty in the face of ever greater institutional demands for greater research and grant productivity. Departments, and offices such as Career Services and Admissions, will also be affected. One would also need to persuade employers—including management, technical, and personnel departments—of the enhanced value of applications with such a credential.

We will note that, although we have presented these as alternatives, these could in principle be used in various combinations as components of a broader interdisciplinary yet focused education. But this would appear to require even more changes in institutional structure, and an agreement among multiple institutions and their faculty, so as to make the components reinforcing rather than repetitive.

We discuss these issues further in [50] and our companion paper in this issue [51].

5. THE IMPORTANCE OF A BROAD STEM PERSPECTIVE

Section 4 has presented a number of perspectives and content areas and argued for a broad education, in particular for STEM professionals. In this section, we look at the interdisciplinary nature of modern STEM and STEM careers. As examples, we consider a number of developments in or affecting the health sciences, and then look at perspectives affecting development of a mobile application interacting with IoT sensors.

Medicine and the health sciences also provide some striking examples. There have been major effects on both theory and practice. A few diverse examples:

- Genetic research has been enabled possible by a better understanding of the underlying science, better models and algorithms, more powerful computer hardware and networks, and tools and techniques developed by biologists, bioengineers, data scientists, and others, and is having major effects [17]. (And conversely, understanding of genetics has led by analogy to genetic algorithms [124].)
- Medical research and drug testing have been under some fire for the lack of diversity in the test population [85]. There have been serious problems and failures in extrapolating the benefits and risks of drugs and medical procedures from, say, active adult white men to women, children, seniors, or people with different ethnic backgrounds. Medicine and the health sciences have had to make additional adjustments to cultural and ethnic differences [41].
- Cumbersome equipment and tests have in some cases been replaced by computer-based systems or techniques based on developments in physics, bioengineering, and biochemistry. Likewise, some surgical procedures have been replaced by laser-based surgical techniques, and/or complemented by non-surgical interventions. For example, laparoscopic surgery has reduced hospital time

as well as complications [60]. Also, while dealing with cataracts was infeasible in the past, laser eye surgery is now routine [114]. As a more complex example, NMR spectroscopy, which can be used to detect protein structures and thus anomalies, relies on quantum physics, engineering of instrumentation, the mathematics of nuclear resonance, computer and storage architecture, algorithms, and data science [5, 64, 69].

- In the practice of dentistry, we see the interaction of materials sciences/engineering, chemistry, laser physics, and medicine in developing families of durable, laser-polymerized composites as a viable alternative to amalgams for filling cavities, saving time, increasing convenience, and reducing possible dangers [107]. In addition, dentists and their patients have benefitted from better x-ray technology, real-time display of x-rays, and visualizations of fittings.
- Statistical analyses and studies of motion and reaction, and of muscle and nerve biochemical processes, have improved cognitive, physical, and occupational therapy, and the internet allows these to be shared easily and on-demand among practitioners. This, together with lessons from physical therapy, improved instrumentation and visualization, has also led to the growth field of sports medicine [74].
- 3D printing and computer graphics visualization, using approaches and guidelines from the arts and cognitive science, including visualizations of the brain, are used to guide consultations and surgery, and are especially useful for remote surgery [95, 101]. Another recent application of 3D printing is bioprinting [32], actually printing tissues and organs, current for research, but eventually for transplantation.
- Patient sensors and monitoring, combined with better models and understanding of many medical conditions, have improved the effectiveness and efficiency of in-facility medical, nursing, and therapist care. Self-monitoring and remote monitoring via computer-mediated and other devices such as Fitbit™ (https://www.fitbit.com/), and more effective and (somewhat) less intrusive devices for monitoring blood sugar in diabetics, have also improved both individual health and medical care.
- Computer-based systems have also improved medical office systems, patient records, insurance claims, and more, across the health sciences, and allowed (at least in principle) records to follow patients from facility to facility and practitioner to practitioner [117].

As an example in the formal sciences, consider a website or mobile app design team for a commercial venture, where the product is to interact with the Internet of Things, for example, an enhanced GPS navigation system [25, 94, 129]. The development team will benefit from an understanding of user expectations and capabilities, which will rely not only on software engineering, but on data visualization and art, cognitive science, learning theory, and epistemology, psychology and sociology, social media and advertising, and economics and marketing. Also important will be an understanding of the delivery system, which relies on computer and network architecture, engineering of mobile devices, the nature and structure of the IoT and its sensors (and if needed, actuators), and security and privacy protections. All of these will affect user acceptance, learnability and usability, performance, reliability, and geographical penetration. There are also legal and ethical expectations, problems to be addressed with business analytics, relying in turn upon databases and data analyses as well as the IoT, and in many cases, knowledge of political and economic trends.

Examples in data science are equally easy to find [123], and, as we remarked above, someone seeking employment in data science will benefit from some knowledge of techniques (from mathematics, statistics, artificial intelligence, and operations research), effective communication (advertising art, cognitive science, computer visualization, and marketing), business practices, and understanding the application domain and its standard practices.

A strong interdisciplinary and multi-faceted approach will afford better professional preparation, and results both in more elegant and effective designs and products, and in academics and professionals who are willing and able to consider the broader effects, including social and environmental effects, of decisions and actions. It supports better communication and teamwork, improving work efficiency as well as effective and informative sharing of information with peers, management, and the public.

Professionals with this background will also be much better prepared for greater responsibility and more complex projects, and for possible transitions into management or other semi-technical roles, and will be better able to contribute as informed citizens and experts to civil and political discourse.

6. CONCLUSIONS AND FUTURE WORK

We believe that this paper has made a persuasive case that even as STEM disciplines become more complex and more focused, STEM students and professionals will benefit from developing skills and acquiring and integrating multiple perspectives, from within STEM and its allied disciplines and from without.

This paper has looked at perspectives and bodies of knowledge, concepts, insights, processes, and techniques that may prove valuable for STEM students and practitioners. We began by considering the STEM movement in primary and secondary education and its variants. Looking at changes in STEM and allied fields, and capabilities identified as desirable for careers and for research, we then presented a structured catalog of complementary perspectives and bodies of knowledge. We then very briefly considered four alternatives for providing that broad and integrated base, a topic more thoroughly explored in our companion paper in this issue. Finally, we looked at how an integrated perspective would benefit a STEM professional in three areas—medical and health sciences, mobile application development, and data science.

In the future, we will develop an integrated view of data science as an exemplar of our perspective, and continue to work for the establishment of graduate certificate programs.

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