Designing the Future of Undergraduate STEM Education: An Inter-institutional and Interdisciplinary Approach

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Abstract

STEM education has received increased attention lately. What has received less attention is *what the substance of STEM education can and should be.* Effective STEM education requires going beyond mere knowledge of STEM disciplines; it needs the development of creativity, ingenuity, and the ability to work collaboratively. Most importantly, it needs a sensitivity to the broader social and the ethical contexts within which we live and work. In this paper we describe the *STEM Futures* project (*stem-futures.org*): a virtual design studio experience for higher-education faculty in STEM disciplines to develop innovative new undergraduate programs and curriculum materials. The goal was to advance visions for STEM education that go beyond the acquisition of content knowledge to integrate creative mindsets and humanistic values. The design studios were organized around a framework (Kereluik, et. al., 2013) that integrates three broad categories of knowledge: foundational knowledge, meta knowledge, and humanistic knowledge. During the studios, more than 100 educators from institutions of higher education across the United States worked collaboratively in teams to develop a diverse and innovative set of curricular design products, including degree and certificate programs, which were designed for a broad array of audiences. Our data suggest that these studios were not just effective and useful, but that the studios also successfully integrated the three broad knowledge domains.

Introduction/Study Context

We are underprepared at multiple levels for the economic, environmental, and societal disruptions that accompany the advance of global civilization and technology. The citizens of tomorrow must be better able to understand, discover, develop, and implement innovative and principled solutions to complex, STEM-infused problems in a rapidly changing environment. Therefore, we need to equip the public at large to become STEM-savvy problem-solvers and to anticipate problems arising from multifaceted challenges: the environmental challenges of the Anthropocene; the economic pressures of machine learning and artificial intelligence; and the social challenges of an increasingly rapid pace of environmental, technological, and economic change.

It is clear that our educational systems need to be reimagined to meet the challenges of preparing the next generation (Denton, 1998; Shepard, Pellegrino & Olds, 2008). Partially in response to this challenge, *how* we teach STEM in colleges and universities is rapidly evolving. For example, evidence-based active learning modalities are being adopted ever more rapidly. Digital technologies are transforming higher education with their ability to expand access and their promise of scaling best practices. The nature and purpose of assessment are being revisited.

Similarly, we are expanding our focus on *who* we are teaching and striving to include a wider diversity of learners. For instance, we are paying increased attention not just to historically disadvantaged groups, but also to the emerging "new majority" of non-traditional college learners (Rendón and Hope, 1996; Klemencic & Fried, 2007).

By comparison to *how* and *who*, we have paid less attention to evolving *what* we teach in STEM programs in colleges and universities—the substance of STEM education (both the explicit and the implicit curriculum) and the pedagogical systems and approaches. Current approaches emphasize certain components but ignore others. STEM courses and degree programs are largely still organized around traditional disciplinary definitions and within traditional boundaries (Martin-Paez, Aguilera, Perales-Palacios, & Vilchez-Gonzalez, 2019), even as the most pressing problems require crossing STEM disciplines and even integrating beyond STEM into other domains of knowledge (Passow & Passow, 2017; Singer & Smith, 2013).

Even when active learning approaches are implemented, current practices still emphasize mastering content and concepts rather than inculcating habits that facilitate creativity (Marquis, Radan & Liu, 2017), critical thinking, problem-solving, or the complex skills and mindsets that allow for thoughtful decision-making and action (Passow & Passow, 2017). Further, this mastery approach remains stubbornly disciplinary, especially at the introductory level, even though, as noted in a 2016 report by the National Academies of Sciences, *Engineering, and Medicine, Barriers and Opportunities for 2-Year and 4-Year STEM Degrees: Systemic Change to Support Students' Diverse Pathways*, students encountering STEM through specific disciplines and departments are often stifled by the course offerings of those departments (see also Benson, Becker, Cooper Griffin, & Smith, 2010; NRC, 2012).

Recent research in communication sciences highlights the need to evolve beyond straightforward concept mastery. For example, science curiosity—the disposition towards wanting to learn and understand the world around oneself—better predicts adults' unbiased reasoning than science literacy when engaging culturally-loaded scientific issues, such as anthropogenic climate change or evolution (Kahan, et al., 2017). Traditional forms of science literacy alone are not enough to meet the evolving needs of a society facing STEM-infused challenges on every front.

Theoretical or Conceptual Framework

We assert that STEM education suffers from a failure of imagination and thus is increasingly misaligned with the challenges we face. To remedy this problem, we organize our thinking about the future substance of STEM education into three broad categories (Fig. 1)—what we need to know, how we act on that knowledge, and the values we bring to our knowledge and action. Taking each in turn:

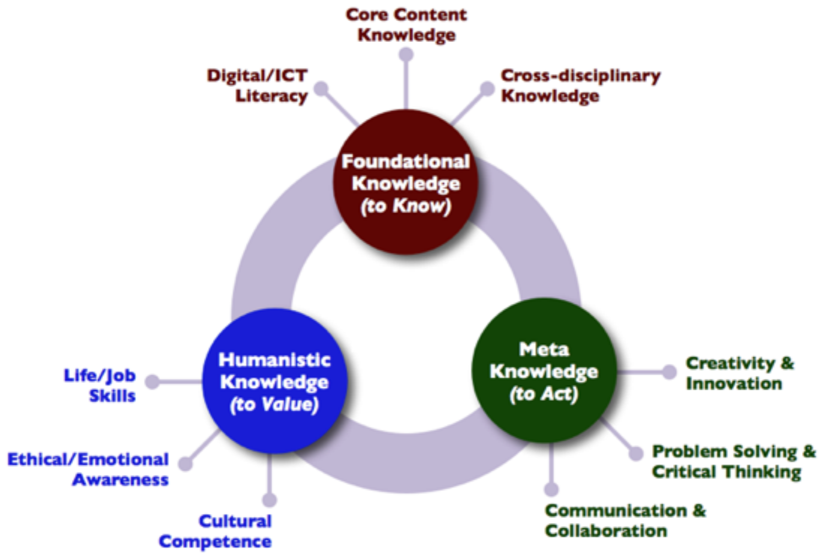

Figure 1. Framework for organizing deliberation on the future substance of STEM education. Graphic from Kereluik, Mishra, Fahnoe, & Terry (2013)

- *Foundational Knowledge (To Know)*: The classic answer to the question: "What do learners need to know?" This includes core content knowledge, skills, and complex, ingrained mental processes specific to domains and disciplines. In the past few decades, emphasis has expanded to include the need for cross-disciplinary knowledge, i.e., information at the boundaries of fields or domains that emerges as vital for application in new contexts (Jesiek, Mazzurco Buswell, & Thompson, 2018). More recently, foundational knowledge has come to include basic digital and information literacy, i.e., the ability to effectively and navigate, obtain, and evaluate knowledge from across a range of digital technologies.
- *Meta-Knowledge (To Act)*: The skills, mindsets, and attitudes that address the process of working with foundational knowledge. Meta-knowledge, in other contexts, are called the "4-C's"—Creativity, Communication, Collaboration and Critical Thinking (Cropley, 2015). Meta-knowledge enables learners to interpret information, make informed decisions, create and design new possibilities, work in collaborative teams, and convey ideas through multiple modalities—to turn knowledge into action (Grimson, 2002).
- *Humanistic Knowledge (To Value)*: These are the values that provide learners with vision and narrative of the self within a social context, from local to global scales. It is the foundation of ethical decision making, and includes life and job skills, cultural competence in a global context (Castaneda, & Meijia, 2018), as well as awareness of how the actions of the individual affects others, and the ability to assess those actions against a set of broader humanistic standards (Lattuca, Knight, Ro, & Novoselich, 2017).

The three categories are complementary, supporting and informing one another; Meta- Knowledge acts on Foundational Knowledge, and is guided by Humanistic Knowledge.

The balance among these categories must evolve in response to economic, environmental, and societal disruptions that accompany the advance of global civilization and technology. Notably, Foundational Knowledge, while important, has in some ways been overvalued in traditional education relative to the other categories. For instance, though problem solving, critical thinking, creativity and collaboration are not unique to the 21st century, advances in technology provide unprecedented access to vast amounts of information. As a result, mastering Foundational Knowledge becomes less important for learners, while Meta-Knowledge—knowledge that permits us to discern high-quality information from information of questionable quality—becomes more important. Humanistic Knowledge becomes increasingly important because technology provides individuals with more power to effect change, placing a greater burden on individuals to act ethically and with an awareness of the complex ways in which technologies can both positively and negatively impact broader society (Pawley, 2017).

Technology has also changed communication and collaboration in crucial ways, providing new opportunities to enhance human creativity and increasing the need for critical thinking. Large-scale communication and collaboration across the globe are now commonplace as a result of increased globalization and affordances of new technology, and consequently individuals from diverse cultures are now exposed to one another on an unprecedented level. This makes successful collaboration—and consequently cultural competence— ever-more essential. In the humanistic realm, ethical and moral questions abound. Whether we consider issues of privacy and intellectual property or bio-technology and stem-cell research, individuals today (and in the future) have to develop fine-tuned ethical and moral modes of thought and action (Berdanier, Tang & Cox, 2018; Huntzinger, Hutchins, Gierke & Sutherland, 2007). In contexts like these, developing a value system that respects differences and yet maintains a core of empathy and understanding becomes critically important (Colby & Sullivan, 2008).

The shifting balance among these categories has implications for the future substance of STEM education. It requires a thoughtful and flexible translation from theory to practical application in the form of core ideas that will then be instantiated within new STEM curricula.

To guide NSF and the wider community in addressing this gap, we hosted a workshop-based program using a design-studio format, hosted by the Office of Scholarship and Innovation at the Mary Lou Fulton Teachers College (MLFTC), and the Center for Education Through eXploration (ETX Center) at Arizona State University (ASU). The central question addressed by this program was: *How might educators reimagine and redesign the content of undergraduate STEM curriculum at the university level to better meet the emergent challenges of the 21st century?* More information about the program as well as all the products generated by the project can be found at https://stem-futures.org

Literature Review

It is increasingly recognized that the nature of science education must evolve in response to societal needs of the now not-so-new century. Policy documents such as *Discipline-Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering* (Singer et al., 2012), *Engaged to Excel* (Olson & Riordan, 2012), and *Vision and Change in Biology Undergraduate Education* (AAAS, 2011) pointed to the urgency for widespread adoption of empirically validated teaching practices and development of broad competencies. For example, *Engaged to Excel* called for active learning approaches using case studies, problem-based learning, peer instruction, computer simulations, and ideally for the replacement of the standard lecture model with discovery-based learning; *Vision and Change in Biology Undergraduate Education* called for developing competencies such as communication and collaboration, understanding the integration of science and society, and systems level approaches. Meanwhile, reports like *Educating a New Majority: Transforming America's Educational System for Diversity* (Rendón and Hope, 1996) have warned for some time about the need to develop more inclusive approaches. The years since these reports have seen shifts in these directions, but mostly in the form of innovations in pedagogical methodologies aligned with traditional, disciplinary STEM learning goals (Hernandez-de-Menendez, Guevara, Martinez, Alcantara, & Morales-Menendez, 2019). Progress is less clear on the more radical challenge of evolving the actual substance of STEM education, especially for undergraduate science majors.

The framework, curricula, and CoP that we sought to develop through this project aimed to provide a pathway to evolve the substance of undergraduate STEM education to better meet rapidly emerging economic, environmental, and societal challenges. We expected that participants would implement the outcomes in their own institutions, so that the program would serve as a springboard leading to widely disseminated changes. Meeting real-world needs, future students–including non-traditional learners–will learn to engage STEM-infused challenges not only by applying disciplinary content knowledge, but also creativity, critical-thinking, and ethics across disciplines.

The format for this workshop employed a studio-based approach, which aimed to find broader application as a result of the visibility of this project. The model emerged as a form of learning appropriate for ambiguous tasks and future or horizon-focused challenges (Brandt, et al., 2013; Brown, 2006). The value of the studio-based approach is that it emphasizes both a process for working, as well as the products that come from the process (de la Harpe, 2009; Ozturk & Turkkan, 2006). This format was particularly appropriate as a vehicle for planning post-workshop efforts to promote curriculum reform efforts through barriers educators in higher education often face, including the inability to test and refine curriculum in environments fundamentally different from the workshop where they start, and the need to create communication opportunities to share with each other which aspects of the curriculum will transfer and under what conditions the transfer will be successful (Henderson & Dancy, 2007).

Project: The Design Studio

The entire project played out in 3 stages: A series of introductory webinars, followed by a week-long series of design sessions where the participants worked collaboratively and iteratively within a scaffolded web-based environment to design their products. Final products were submitted approximately two weeks after the end of the program. Participants were surveyed both before, during, and after the end of the project and these surveys were used to tweak the design of the sessions. More information about the project, as well as embedded videos of the webinars, videos introducing the scope and plan of the project, as well as all the products generated through these collaborative studios can be found at https://stem-futures.org

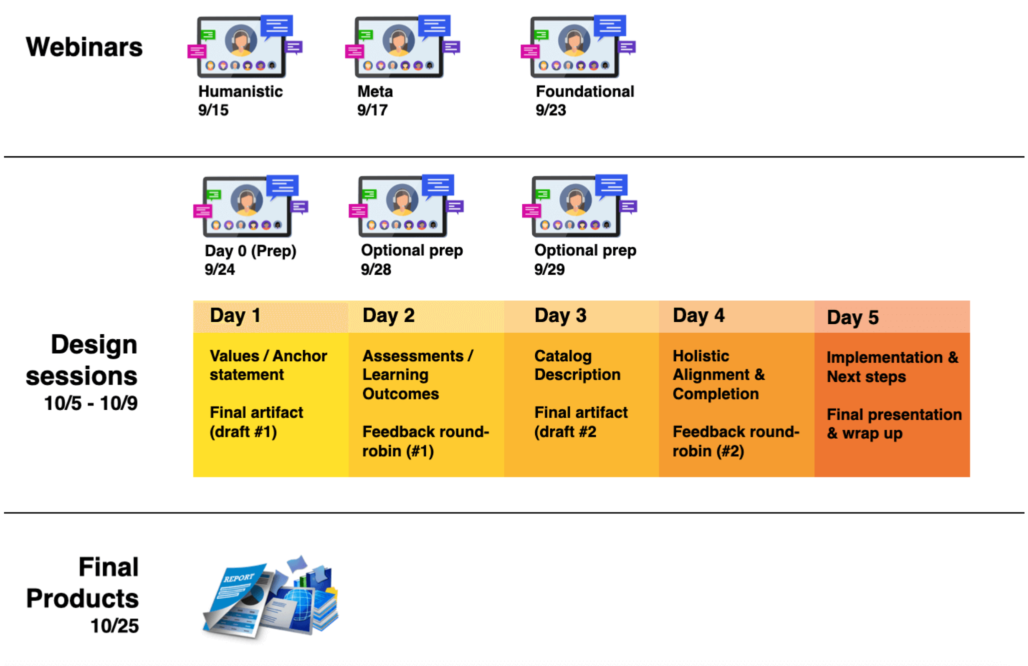

Figure 2. Framework for the workshop organizing structure.

The design-studio workshop was preceded by four webinars that explored the framework and set the stage for the design sessions. The first three webinars introduced and explored the framework while the fourth set the stage for the design sessions. It is important to note in this context that though the first three webinars were each framed around one component of the framework, the discussion was usually integrative in nature—connecting across the domains for foundational, meta, and humanistic knowledge.

The workshop adopted a design-studio format, in which participant teams were tasked to create future STEM program concepts, and then scaffolded into iterative rounds of work and feedback. The meetings were conducted over Zoom with sessions that alternated between all group and small group meetings. The work was scaffolded by an online platform (Serckit) designed and maintained by Carleton College's Science Education Resource Center (SERC). Serkit allowed participants not just to synchronously collaborate on their projects but also to see and comment on the work being done by other teams. A strong emphasis was also placed on creating a sense of community and collegiality even while maintaining high expectations and standards.

105 individuals, accepted from 179 applicants, formed into 25 teams. Most individuals applied as part of pre-formed teams, while others were placed into new or pre-formed teams after their acceptance. Participants represented 53 different institutions from 29 U.S. states. They were 65% female, and 32% persons of color or otherwise underrepresented minority.

Methods

We employed a mixed-methods approach to data collection and analysis. We administered surveys to participants and analyzed the data using descriptive statistics. Additionally, we examined the content (substance) of STEM curricular design products from twenty-five teams through in-depth content analysis.

Surveys

For survey participants, a total of six optional surveys were distributed to participants. The first survey took place at the end of the fourth and final pre-workshop webinar, and consisted of ordinal ranking questions on a 1-10 scale to determine participants' understanding and preparedness for the weeklong workshop. Once the workshop began, five daily surveys were distributed to participants at the conclusion of each day's programming. Presented as "roadchecks" for the first four days, these surveys included ordinal ranking questions on a 1-10 scale, asking participants to gauge general satisfaction with the workshop, as well as items inquiring on the progress and sense of success the participants felt they were making toward their workshop product outcomes. Each roadcheck also included optional open response space for participants to provide feedback to workshop organizers. On the fifth and final day, an overall workshop evaluation was conducted to gauge participants' overall satisfaction with the workshop, its delivery and format, and their perceptions of value related to what their teams produced (*"How satisfied were you with your team's final product"*).

Content Analysis

Content analysis sits at the intersection of qualitative and quantitative methodologies. For this project, we began by extracting the goals and learning outcomes from all 25 projects. Two of the researchers read through the material for each project. Then, we coded the components of the goals and learning outcomes that were related to the conceptual framework: foundational, meta, and humanistic knowledge. While coding, we also applied an interpretive lens (Krippendorff, 2019) and wrote thematic memos. After coding the first 10 projects individually, we met together to discuss any discrepancies and the themes that seemed to be emerging from the analysis. For the first 10 projects our interrater reliability was .95. Once we completed the final 15 projects, we met again to discuss any discrepancies and further discuss potential themes from the data. Our overall reliability was .90 but all discrepancies were addressed and a final coding decision was made. The themes that emerged originally were ethics, integration of multiple disciplines, a focus on community, and the use of design-based learning experiences, diversity, equity, and inclusion, and a focus on personal and professional skills.

NVivo, a qualitative analysis computer software package, was used for an additional layer of analysis. The goals and learning outcome components of the curricular products were analyzed using an exploratory one word analysis for both exact matches and stemmed words. For example, stemmed words for culture include cultures and cultural. Words appearing on the top 100 list were then used to triangulate the data and emerging themes from the original coding completed by the researchers. Text search queries were completed on key words from the NVivo analysis to see how those words were being utilized within the text for a final layer of analysis.

Results

Participant feedback (n=59) was overwhelmingly positive (overall satisfaction averaged 9 on a 10-point scale), with a preponderance of participants seeing it as a valuable experience. Participants also cited the design of the sessions as providing them with both the flexibility to work with and learn from others. They also cited the deeply meaningful nature of the work itself as a contributing factor to the success of the workshop, and were also grateful for being able to participate in an emergent community of like-minded STEM educators.

Participants, in particular, reported the importance of the conceptual framework and the webinars for setting the stage for the workshop's design sessions. Most participants believed that their projects integrated the three forms of knowledge quite well *with 90% of the participants reporting substantial or total integration of the meta and humanistic aspects of STEM education*. Furthermore, many participants indicated that they would continue to work together on the projects and move them towards actual implementation with some teams exploring further funding, emergent publications, and more.

The purpose of these diverse and innovative curricular design products was to push STEM education beyond content knowledge and include the mindsets and values that will help STEM professionals be ready for the work, environment, and decisions that lie ahead in their career. By analyzing the content of the curricular design products through the knowledge framework, our goal was to understand the programmatic characteristics and themes across a curriculum-making experience with an intentionally more holistic approach to include foundational, humanistic, and meta knowledge. The programmatic characteristics and foci that came out of this content knowledge will help us better prepare STEM professionals, design more relevant STEM curriculum, and begin to change the conversation of what it means to be a STEM learner or STEM professional.

Initial results from the content analysis yielded outcomes similar to the survey results: 88.5 % of the projects integrated all three forms of knowledge, 7.7% integrated two forms, and 3.8% predominantly focused on one category. The final products of the workshop included a diverse and innovative set of curricular design products, including: 6 degree programs, 9 certificate programs, 7 efforts for courses, course components, or curricular alignments, and 3 training and professional development programs. These efforts spanned traditional disciplines such as Biology, Chemistry, Geology, Engineering, and the Health Sciences, as well as more interdisciplinary STEM programs. These diverse teams designed their materials for a broad array of audiences including STEM majors and non-majors, first-year students, disciplinary majors in upper-level courses, college faculty, preservice teachers, student leaders, and college STEM-bound high school students. The summary that follows outlines the themes, word frequencies (and ranks), and excerpts from the curriculum products (Table 1).

Theme	Example of Related Top 100 Words [Rank]	Frequency	Excerpt from Curriculum Products
Integrating varied disciplines with STEM [Foundational Foci]	STEM [3] Integrate [21]	85 26	↦ Examples of STEM disciplines: biology, chemistry, geology, engineering, and health sciences, and interdisciplinary STEM foci; ↦ Examples of Non-STEM disciplines: arts, history, humanities, philosophy, economics, law, political science, and geography
Ethics integration into the learning [Humanistic Foci]	Ethics [8] Values [12]	47 38	↦ Scenarios that require ethical reasoning to make choices; ↦ Ethical technology development; ↦ Incorporate 8 characteristics of ethical reasoning
Creating design-based learning experiences to solve problems in community, society, world [Meta and Humanistic Foci]	Community [9] Problems [10] Social [16] Indigenous [29] Solutions [30] Agent [50]	47 41 32 18 17 9	↦ Develop strong partnerships with community; ↦ Co-design solutions to societal issues; ↦ Be agents of change; ↦ Focus on underserved, high-need populations
Intentionally including additional types of thinking [Meta and Foundational Foci]	Thinking [15] Research [17] Design [19] Scientific [12] Systems [23]	32 29 28 24 23	↦ Use design thinking to innovate and iterate toward solutions within these complex systems; ↦ Use systems thinking and STEM tools to model complex systems; ↦ Futures thinking to envision desirable and possible futures

Focusing on social and emotional learning and professional skills [Humanistic Foci]	Communicate [24] Professional [37]	22 12	↦ Emotional self-awareness words: empathy, personal freedom, autonomy, identity; ↦ Social awareness words: conflict management, communication, fairness, justice, inclusion, equity; ↦ Professional skills: leadership, dealing with ambiguity, adaptability, curiosity, ethical-decision making
Valuing and addressing diversity, equity, and inclusion issues in STEM [Humanistic Foci]	Culture [20] Diversity [25]	28 20	↦ Issues of diversity and inclusion in healthcare and STEM fields; ↦ Implement practices that support inclusivity and diversity; ↦ Diversity of stakeholders are valued

Table 1. Themes and Curriculum Product Excerpts

Figure 3. Word cloud of stemmed words

Illustratively, *community* was a salient focus (Fig. 3), i.e. connecting and situating STEM as being an integral part of society, especially within local communities, was a critical component of many of designs. Design-based learning experiences where learners co-designed solutions to societal problems was evident across the different programs. This connection allowed learners to act as "levers of change" and demonstrated how the future of STEM is deeply entangled with broader societal issues. The issues addressed varied across projects to include: environmental issues related to earth processes, food safety, diversity and inclusion in healthcare and STEM fields, responsible conduct of research, cancer prevention, and societal and genetic differences that impact human health.

Discussion

One of the goals of the project was to advance innovative visions for STEM education that go beyond the acquisition of core content knowledge to integrate mindsets and values. The integrative framework (meta, humanistic, and foundational knowledge) grounded the conceptualization of the twenty-five unique curriculum designs. Our analysis showed a prevalence and increased importance of integrating humanistic knowledge across multiple program artifacts, with an emphasis in situating experiences and ultimately solutions within and for communities. The critical need for target learners or stakeholders to understand the importance of ethical concerns, and to be fully aware of the complexities of the societal problems that they are being trained to address, were also well-documented (Pawley, 2017). This focus on ethics, ethical reasoning, and ethical action across multiple programs was notable and encouraging. Similarly, meta knowledge was well-integrated across various program components as well.

We believe that there are a few key takeaways from this work. First, we found the workshop's conceptual framework, which integrates foundational, meta and humanistic knowledge, to resonate positively with STEM educators as a way to account more fully for the kinds of knowledge we anticipate needing in an increasingly complex and uncertain world. Based on participants' use and feedback during the workshop, we expect that future adoption and use of this framework might encourage educators to explore the creative connections and possibilities at the intersections of the knowledge categories within the framework. Second, the design studio approach of the workshop may be useful for future delivery where educators are working in teams to create and design new curricular frameworks. Finally, we believe the workshop itself may serve as a model for future curriculum development, particularly in a world where distributed and remote collaborations are likely to continue.

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