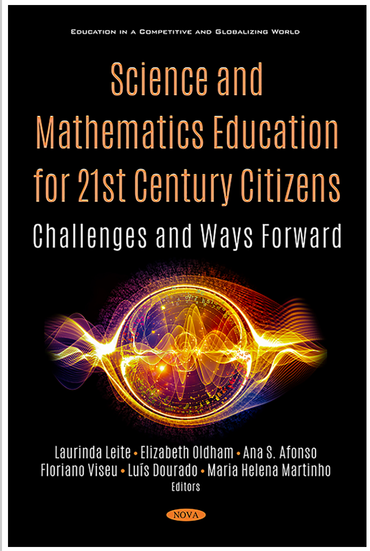
Book review: Facing 21st century challenges with cutting-edge math and science education

By Shalin Hai-Jew, Kansas State University

Science and Mathematics Education



Details

Science and Mathematics Education for 21st Century Citizens: Challenges and Ways Forward
Laurinda Leite, Elizabeth Oldham, Ana S. Afonso, Floriano Viseu, Luĩs Dourado, and Maria Helena Martinho
Nova Science Publishers
2020 407 pp.

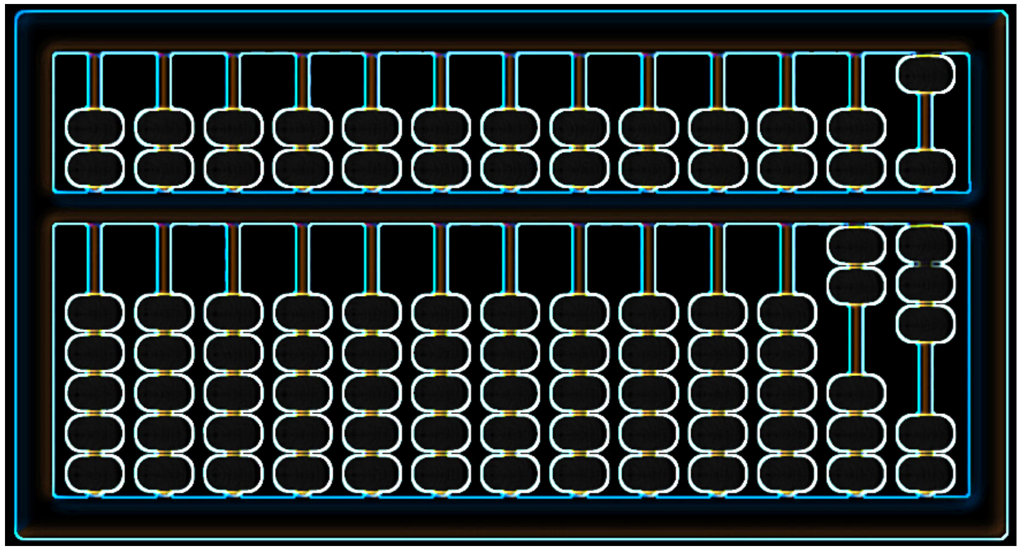
Laurinda Leite, Elizabeth Oldham, Ana S. Afonso, Floriano Viseu, Luĩs Dourado, and Maria Helena Martinho's edited collection *Science and Mathematics Education for 21st Century Citizens: Challenges and Ways Forward* (2020) strives to offer ways forward to developing human capital by advancing science and math knowledge. This is for the few who will innovate and contribute fundamentally to the betterment of human life. This is for the general populations who can align behind science for improved human health and a healthier and more sustainable environment.

This collection was inspired during the 2019 Association for Teacher Education in Europe Winter Conference. A short year later, this collection offers educational programs for teachers, research, new pedagogical models and methods, and ways to build the capabilities of people and infrastructures for new generations.

Building a Nation's Intellectual Capacity

In the Foreword by Peter Aubusson at the University of Technology in Sydney, Australia, he suggests that STEM is not only about national competitive advantage but serves as "a de facto measure of a nation's intellectual capacity" (2020, p. ix). In this context, it is more important than ever to focus on new thinking and methods for the teaching and learning in STEM.

Abacus (by ArtsyBeeKids on Pixabay)



Details

Figure 1: Abacus (by ArtsyBeeKids on Pixabay)

21st Century Skills = ?

Elizabeth Oldham and Elsa Price, in "Teaching and Learning Science and Mathematics in the 21st Century: Challenges and Aspirations" (the Introduction), explain the criticality of higher-order thinking skills or those that enable people to function into the future. They write:

In a rapidly changing world, one thing that we know is that people will have to cope with studying topics and acquiring skills that are as yet undefined. Learning subject-related facts and routines may be much less important than developing higher-order skills—so-called 'key skills' or '21st century skills'—that transcend subject boundaries. These are deemed to equip people to be good citizens, able to live comfortably in and contribute to the societies of which they are part. (p. xv)

There are debates about what so-called 21st century skills entail. There is certainly an important citizenship and professional ethics component, in addition to the economic one. The concept of 21st century skills is almost generic even as it has been addressed directly in the academic literature in a prior book, *21st century skills: Rethinking how students learn*, by James Bellanca and Ron Brandt in 2010.

Limited global generalizability of research findings? In a complex global environment, the borrowing of policies from other locales may not be particularly effective. The authors cite a work that identified four areas of challenge, which they summarize as follows:

> Political: can the use, or rather misuse, of results be controlled?
> Methodological: is the theory adequate and are its assumptions fulfilled?
> Curricular: do the studies adequately reflect participants' curricula in design and reporting?
> Pedagogical: can we learn from very different cultures (Kaiser, 1999, as cited in Oldham & Price, 2020, p. xviii)

They cite research which suggests that the answer may be "no" in many cases above. These negative findings suggest that more attention needs to be paid to mitigating potential negative effects of research in the political space. More thorough theorizing and understandings of theoretical implications would be important. The studies need to be precisely described to reflect what the curricula actually is. And this would suggest that harnessing findings from other contexts should be done carefully and in nuanced and empirically tested ways. There are issues with the adoption of technologies in the STEM learning space. The design of authentic learning, such as through problem-based learning, also requires thought-through designs and deployments. The

coauthors observe the realities of the present moment in the COVID-19 pandemic. "This offers a forceful illustration of the value of science, mathematics and technology in addressing challenges that face the world" by informing on the "nature of the COVID-19 virus and providing us with an understanding of topics such as immunology, mathematical modeling of contagious disease spread, data graphs, and protective technological innovations (Oldham & Price, 2020, p. xxiii).

Strengthening Teachers through Continuing Professional Development for STEM

Aibhín Bray, Jake Rowan Byrne, and Brendan Tangney's "STEM Continuing Professional Development for 21st Century Teaching and Learning: The Bridge21 Approach" (Ch. 1) showcases a pedagogical model for building STEM learning in Irish secondary schools. "21C" or 21st century learning is thought to require "development of skills such as problem solving, critical thinking, collaboration, communication and creativity" among others. Various educational reforms are ongoing to build towards the future. Bridge21, the evaluated pedagogical and activity model, includes teacher continuing professional development (CPD) opportunities including in virtual immersive spaces (p. 3) and around topics such as computer programming, math, physics, and others (p. 4). Teams are brought together to work together to solve a particular challenge and then co-create some teaching contents (p. 6). The lesson activity model involves the following steps: set up, warm up, investigation, planning, creation, presentation, and reflection (p. 7). The work is supported with lesson-planning templates. There are procedural steps to consider the following (and others): "the rationale for the learning experience; a description of the activity; identification of Bridge21 components utilised; key skills covered; curriculum content covered; assessment of students; the resources/scheduling required" (p. 8). The learning occurs as a structured process and in group activities.

This chapter includes two learning examples. One is an "orienteering" approach to a math lesson (p. 10) to concretize some ideas of math plotting (with the idea that too much abstraction in math is not conducive to learning). Here, a grid overlay is placed over a school map. Students in groups capture QR codes at different physical locations at the school. "…scanning each QR code generated the geometrical transformation that the students had to perform in order to locate the next base" (Bray, Byrne, & Tangney, 2020, p. 11). (For this reviewer, this seems like trying to make something fun more than about enabling in-depth learning.)

Another learning example from the Bridge21 method involves the posing of a question to spark inquiry-based learning: "Is water from the local river (Dodder) safe to drink?" (Bray, Byrne, & Tangney, 2020, p. 12). This question was posed to 14 – 15 year-old students participating in an 8-week after-school science club. Their work involved understanding water quality with limited equipment: a toolkit "containing a universal Ph indicator, a pooter (a small jar with a lid for collecting insects), a light meter and a plant and animal identification key" (p. 13) as well as a smartphone camera and access to a school science lab. The students conducted a "habitat study on the river bank" (p. 12). The tools do not seem particularly aligned to the posed question. However, the learning may have been more about hypothesizing and gathering information and reasoning. The participating students finally presented their findings on the online Padlet app.

Finally, the researchers conducted qualitative and quantitative research to assess the respective Bridge21 modules for efficacy. This approach looks like an effective way to advance teaching methods for 21st century skills.

Sustainability Literacy by Empowering Teachers

People, no matter what countries they are part of, are also global citizens. They all have some responsibility for preserving the larger natural ecosystem both for themselves and future generations. Humanity, writ large, is facing challenges with drought and water usage, climate change, biodiversity loss (from habitat loss), energy challenges, food production challenges, and various natural hazards (including pandemic-level viral spillover threats). The natural world, in parts, is hostile to human life and will require concerted efforts to ensure the livability of the planet.

Leaves Lungs (by RoadLight on Pixabay)

Details

Figure 2: Leaves Lungs (by RoadLight on Pixabay)

Doris Elster's "Education for Sustainability Literacy: A Challenge for Teacher Education" (Ch. 2) also begins with the premise that supporting teachers is a net positive for teaching and learning. The idea here is that teachers with sustainability literacy training can infuse sustainability into their curricula and taught values. They can uphold Education for Sustainable Development (ESD), which resonates with both science and social justice, and is part of Agenda 2030 goals. This work provides a summary of the provenance of the political ideas towards global sustainability in education, then how it has instantiated in Germany at the national level. She summarizes some of the animating pedagogical ideas, such as "active self-determined learning" (p. 35).

She shares some ideas for the teacher competencies: "The vision is to build a capacity for teachers to be able to approach the broad and complex nature of sustainability and the problem-oriented, solution-driven nature of sustainability, as well as how sustainability connects to them as both citizens and classroom teachers." (p. 36) The ideas are expressed in the Sustainability Education Framework for Teachers (SEFT) (Warren, Archanbault , & Rider, 2014, as cited in Elster, 2020, p. 36). This framework is said to combine "futures, values, systems and strategic thinking" (p. 37) to help with mass-scale problem solving. This work inspires with the complexity of national-level plans and the clear bureaucratic and planning work which went into these programmatic efforts.

Teaching to Emotions in Science

Pedro Membiela, Katherine Acosta, Antonio González, Manuel Vidal, and Miguel Ángel Yebra's "Emotions in the Teaching of Science" (Ch. 3) focuses on questionnaires completed by 126 inservice teachers in Early Childhood, Primary, and Secondary education in Chile during the 2017 – 2018 academic year. In alignment with much of the research literature, these co-researchers reaffirmed the importance of the teachers' emotional experiences when teaching, in their ability to teach, to motivate, to maintain classroom order, and other essential work. The researchers explored correlations between teacher emotions and other dimensions in the work:

> The correlations between enjoyment and the positive dimensions (Expertise as teacher, Relevance of teaching science, Self-efficacy teaching science, Actual teaching science, Teacher's comfort towards science, Child benefit toward science, Satisfaction with teacher's choice) were positive. Conversely, the correlations between the positive dimensions and anger and boredom were negative. Furthermore, the negative dimensions (Difficulty in teaching science, Gender stereotypes in teaching science) correlated negatively with enjoyment and positively with anger and boredom. (p. 47)

Certainly, some variables have effects on teachers' emotions. "Teacher's comfort towards science, Child benefit towards science and Satisfaction with teacher's choice" act to protect the teacher from negative emotions and enhance positive emotions (p. 47). A core precept in this work is that science is not a "dispassionate and emotionless pursuit" counter to some stereotypes (p. 55).

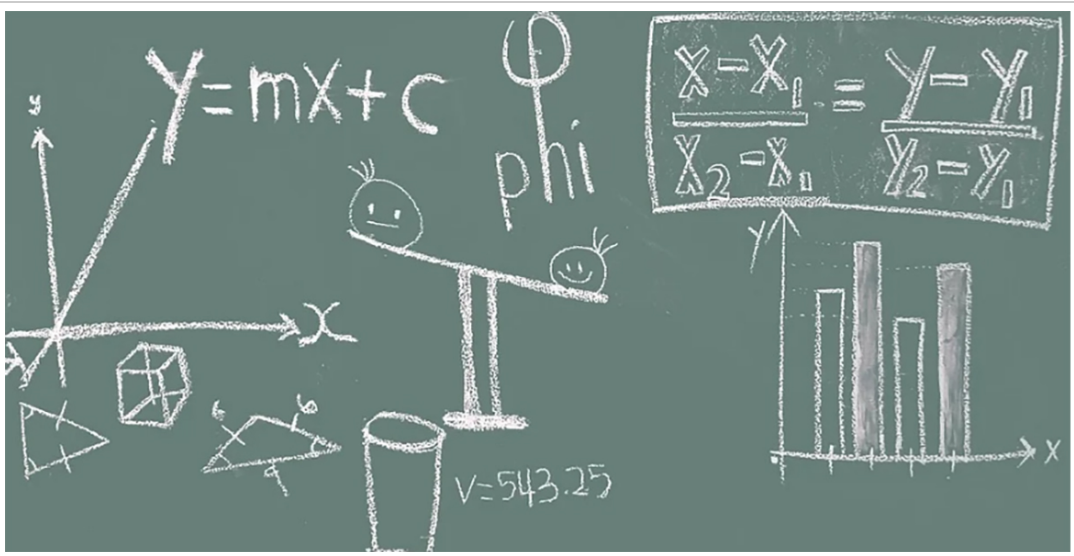
The study of emotion in learning has mostly focused more on learner emotions than teacher ones. Emotions may be informed by dispositions but also the larger context; they may be informed by a complex interplay of factors. For effective teaching and learning to occur, the teacher-student relationship is an important one. Teacher frustrations may be evoked from student misbehavior, for example. Teachers need to regulate emotions as part of the work but "hiding and faking" emotions were related to emotional exhaustion and harm to physical health (Taxer & Frenzel, 2015, as cited in Membiela, Acosta, González, Vidal, & Yebra, 2020, p. 49).

This research team did find a correlation between antecedents and emotions, specifically that there was a positive association "between enjoyment and the positive antecedents (Working with children / adolescents, Expertise as teacher, Teacher social status, Relevance of teaching science, Self-efficacy teaching science, Actual teaching science, Satisfaction with teacher choice) whereas anger and boredom correlated negatively with the positive antecedents. Complementarily, the negative antecedents (Difficulty teaching science, Gender stereotypes) showed negative correlations with enjoyment, and positive relationships with anger and boredom. The only exception was the correlation between Difficulty of teaching science and boredom, which, albeit low and non-significant, was negative. (Membiela, Acosta, González, Vidal, & Yebra, 2020, p. 58) Some of the bivariate correlations of emotions with other variables could be better explored. One practical suggestion is to protect teachers against negative emotions "to promote job satisfaction with regard to science teaching" (p. 60), such as by lessening workloads (p. 61).

Physics and Mathematics in Motion and Function Graphs

Maria Alessandra Mariotti's "Motion and Function Graphs: An Example of Interplay between Physics and Mathematics at School" (Ch. 4) argues, based on historical and epistemological approaches, that mathematics and science should be better integrated and not treated as separate and disparate disciplines. Currently, people tend to observe "the distinction between disciplines," which are treated as "well settled," and professional expertise tracks and sequenced course listings (p. 72) in a siloed way. In the new rethinking, people practice Interdisciplinary Mathematics Education (IdME), and a more integrated sense of math in STEM studies. As a starting point, the author describes the wrangling with formulaic and graphical mathematical expressions of velocity, a concept with presence also in physics (pp. 74 – 76) and using this as a basis to create a learning sequence for "model-eliciting activities" (MEAs) for learning about velocity, including the uses of a dynagraph and a sensor (p. 81), live simulations with human timers (p. 83), and other approaches. Here is a lived sense of showing integrated math and physics.

Math Blackboard (by Pixapopz on Pixabay)



Details

Figure 3: Math Blackboard (by Pixapopz on Pixabay)

Creativity in Science Teaching: Applied Methods from the Academic Research Literature

Agustín Adúriz-Bravos "Innovative Strategies for Science Teaching" (Ch. 5) involves a deep review of the literature and then the identification of five central creative approaches in science education: "those involving the use of analogies, argumentation, models, enquiry, and narratives" (p. 91). The author identifies these methods as being student-centered, active-learning focused, humanistic, and citizen-centered.

He provides some examples of analogies (1) in science education:

> A type of analogical model widely used in science classrooms is what could be called 'scientific representation': a visual representation on data obtained with instruments and processed with computers. For instance, satellite images, electrocardiograms, seismic tomographies, karyotypes, etc. Complementarily, another kind of analogical model is constituted by 'concrete representations'—conventional visual representations that *indirectly* involve empirical data. For example, ball-and-stick molecular models, a sketch of an electrical circuit, a computer animation of the Solar System, scale models of cells, etc. (Adúriz-Bravos, 2020, p. 96)

Powerfully, he shares Galagovsky's (2003) four "moments" of leading students through the analogy, in the "transportation of content between source and target" (p. 97): moment of the source, moment of conceptualization, moment of correlation source-target, and moment of metacognitive reflection. Analogies only apply to a degree, and it should be clear how they apply.

He does likewise with the other creative approaches. He reviews argumentation (2) in science, solid epistemic methods for such, te use of data and proofs, the uses of language, and the cultural situatedness of such work (Adúriz-Bravos, 2020, pp. 98-99). For school scientific arguments (3), the author suggests that there are four required elements: theoretical, logical, rhetorical, and pragmatic (p. 99). In modeling, how the world is represented comes to the fore. These change over time as new information is acquired, to enable the integration of the new understandings. The modeling is conceptualized as subjective and objective. He writes:

> If teachers structure school activity around theoretical models, they would be introducing in the classroom a corpus of disciplinary knowledge that can be seen as human heritage. But, as it was pointed out above, such introduction should not be naively designed as a 'rediscovery' of complex ideas that took centuries of collective hard work. It should rather be proposed for students as a constructive and mediated internalisation of intellectual tools that are *cultural* in their nature, presenting them in the science classroom with the level of formality required for each problem and for each stage of learning. (p. 101)

A new pedagogical approach is "enquiry" (4) which is defined as "a non-linear process where students *explore* the world to ask questions, methodically *investigate* phenomena to get evidence, and publicly *share* abstract, general ideas that give satisfactory answers" (p. 101). He suggests framing scientific inquiries in ways that amplify the work, such as bringing up analogical "detective investigation, medical diagnosis, forensic work, and ...garden-variety thinking" as contexts (p. 103). Adúriz-Bravos suggests that science storytelling or narration (5) would make science practices more accessible. Here, the storytelling would be multimodal and collective, with various explanatory elements (pp. 103 – 104).

The prior five methods here have strong theoretical foundations and are sustainable, he notes, and could benefit science didactics with further usage and documentation.

From Makerspaces to Classrooms for Innovations

One way to enliven classrooms is to bring in aspects of the larger world into this controlled learning space. In terms of 21C skills, so-called "makerspaces" (2005) are like "shops" where people can work alone or together with others to create designs, simple machines, and other functional objects. Digital fabrication, such as through the uses of 3D printers and laser cutters, are part of many makerspaces. Introducing makerspaces into the classroom is seen as a net positive in Susanne Walan's "Transfer of Activities from Innovative Environments such as Makerspaces to Classrooms" (Ch. 6), even as there are challenges in implementation.

Solder Space (by digitalskennedy on Pixabay)

Details

Figure 4: Solder Space (by digitalskennedy on Pixabay)

In a European conference about makerspaces, these approaches have a variety of objectives, such as "supporting social innovation, inclusion, lifelong learning, creativity, or arts and culture; developing skills, including digital skills, engineering and entrepreneurship; and boosting innovative education in schools" (Vuorikari, Ferrari, & Punie, 2019, as cited in Walan, 2020, p. 115); however, there has not been as much found bridging to formal science learning. Makerspace culture and school cultures are different, with the first more about doing STEM than directly learning STEM. The first hails from informal learning, and the latter from formal and accredited learning. Teachers themselves may not have the sufficient STEM background for some makerspaces (p. 116). Sometimes, the costs of the materials may be prohibitive (p. 117). The equipment itself is not low-cost, in some cases, and programming may be "overly complex" (p. 111). Still, early exposures to some of the science and technologies in the world may spark interest, sometimes even for a lifetime.

Artificial Intelligence (by geralt on PIxabay)

Details

Figure 5: Artificial Intelligence (by geralt on Pixabay)

In this study, teachers were invited to a professional development programme at a makerspace in Sweden. They engaged in a variety of activities, such as "coding and making objects to solve different problems using various construction materials and equipment such as microbits and 3D printers" and using Scratch to make a basic game and designing a "pole house" that would stay balanced when a weight was placed on it, and others (Walan, 2020, p. 117). Then, these participating STEM teachers were asked about their experiences, including their assessment about the makerspace value in STEM learning for 21st century skills, and the challenges they faced. The use of Scratch has been identified as useful for introducing learners to the fundamentals of programming (p. 124). It does look like a science-learning approach has to be built into any makerspaces applied to STEM learning in formal classrooms since these are not inherent to the activities.

Exploratory Mathematics Teaching…and a Case of Rational Numbers

João Pedro da Ponte and Marisa Quaresma's "Exploratory Mathematics Teaching and the Development of Students' Use of Representations and Reasoning Processes: An Illustration with Rational Numbers" (Ch. 7) focuses on an inquiry-based math teaching method in which learners work on tasks "that may lead to the construction of new knowledge" (p. 131). This is a context where the teacher "does not directly teach procedures and algorithms, present explanations, show examples and propose exercises to students to practice, but, instead, suggests the students…work on tasks that lead to the construction of new knowledge" (p. 132). In the process, the learners build new skills and an inquiry approach to the world.

This research involves five such lessons to students in "a grade 6 class in a deprived rural area at 50 km from Lisbon" and with parents who have completed "grade 6 or grade 9 only" (Da Ponte & Quaresma, 2020, p. 136). The five 90-minute classes in which the exploratory approach is applied were video-recorded and transcribed. One prompt reads verbatim:

> 2/4 is greater than 1/3, 4/5 is greater than 3/4. Can we make the following statement: "if we want to compare two fractions and verify that one of them as the numerator and the denominator greater than the other, can we immediately conclude that such fraction is the larger one? Justify your answer." (p. 137)

The students took various methods to arrive at counter-examples to refute the fallacious assertion. The coauthors show some of the student work and quote them in their articulation of findings. They share some of the dialogue between students and teachers.

Some prompts are story problems. There are common issues of quantitative equivalencies and substitutions, common logics in math. Sometimes, such inquiries may be achieved by the whole class together, in concert and interactions with the teacher. Other times, inquiry-based learning may be done in groups or pairs. Some sessions may be phased ones.

This chapter is engaging, with a fine attention to details about teaching and learning and ways to improve. Teaching itself is already very demanding, and many practitioners do not have the mental space to add pedagogical research into the mix. Still, there has to be space for the discoverability of new methods.

Developing Critical Thinking and Inquiry Skills in Children

What would learning look like if children were trained to think like a scientist? What would societies look like if they were acting based on a mass-scale scientific-thinking sort of massmind? Such is the vision of Jan Visser, as described in Shanshan Ma and J. Michael Spector's "Preparing the Next Generation of Scientific Thinkers: Developing Inquiry and Critical Thinking Skills in Children" (Ch. 8). In this work, the coauthors describe the history of "scientific thinking," with various definitions. While some tie this capability to particular domains, others take a more generalist view. For example, scientific thinking is about observation, inquiry, critical thinking, science-based reasoning, open-mindedness, and innovation (p. 156). In many ways, it is about how people engage the world. The next generation science standards (NGSS) suggest that scientific thinking is comprised of "practices, disciplinary core ideas, and cross-cutting concepts" (Ma & Spector, 2020, p. 157), which may inform pedagogy. The science pipeline is seen as particularly risky of dropout in the transitions to middle school and to high school, when interests dwindle and other competing interests come to the fore. The National Research Council (2012) defined the "practices dimension" in eight steps: "1) Asking questions (for science) and defining problems (for engineering), 2) Developing and using models, 3) Planning and carrying out investigations, 4) Analysing and interpreting data, 5) Using mathematics and computational thinking, 6) Constructing explanations (for science) and designing solutions (for engineering), 7) Engaging in argument from evidence, 8) Obtaining, evaluating, and communicating information" (Ma & Spector, 2020, p. 157).

From this earlier thinking, the authors propose a nine-phase framework is created to help develop inquiry and critical thinking in children. As presented in 2018, it involved the following steps: "Inquiry and puzzlement, Exploration and hypothesis formation, Evidence and hypothesis testing, Influence and causality, Explanation and communication, Coherence and consistency, Assumptions and biases, Perspectives and alternatives, (and) Reflection and refinement" (p. 159). Since then, the thinking has evolved further. The authors describe a game prototype in which learners can explore thinking among people in an ecosystem to get to a confirmable hypothesis. They point to interactive technologies that may expand automated learning in various scenarios designed to their framework for inquiry and critical thinking.

Scientific thinking is a long-term endeavor, with such capability thought to be not fully developed until well into adulthood. Along the way, children have to be nurtured and supported to develop the science-based habits of mind and practices. This is not about rote memorization of prior discoveries per se but enablements to move beyond what is presently thought (current paradigms, which are constantly under challenge). Finally, this work does evoke how hard it is to build a complex and resilient and productive knowledge-set in people, which explains some of the disparities between wages, and also why there is so much aggressive head-hunting of talent. (This also explains "Operation Paperclip" from WWII.)

Harnessing Educational Robots for Teaching and Learning

Theodosios Sapounidis and Dimitris Alimisis' "Educational Robotics for STEM: A Review of Technologies and Some Educational Considerations" (Ch. 9) focuses on some of the more concrete (analog) and abstract (coding) approaches to learning about technology. The coauthors review the literature related to educational robots. They extract seven general categories of such robots: "Do It Yourself (DIY) robots; open hardware robots; brick-based robots; pre-assembled robots; only for simple actions or specific purpose robots; humanoid robots; robots-based on tangible programming" (p. 173). They consider how much guidance should be offered in the learning. Should it be strong or weak guidance (p. 169) to manage learners' cognitive loads? When in a sequence should particular guidance be offered? And how should learner collaborations be structured? This work also suggests the importance of introducing robotics earlier to children to avoid the negative effects of gender and cultural stereotypes on people's self-identities (p. 171). Finally, beyond the benefits of so-called "guidance scripts" and "collaboration scripts" by the teacher (and/or system) in deploying educational robots, this work suggests that there are challenges to setting up robotics kits, programming various actions, and testing—to integrate educational robots effectively for learning.

Virtual Hands-on Science Learning

Richard Lamb's "Virtual Reality as a Tool for Improvement of Hands-on Science Learning" (Ch. 10) explores some of the promise of virtual labs (in 3D) by enabling immersive learning and repeatability of the lab experiences (with "soft failures". The research here involves 112 faculty, who represent 336 lab sections and some 10,000 students in the undergraduate life sciences, who pilot-test a VR-based lab. The assessment of such learning tools are based on a variety of factors: the relevant technical information, pre-lab lesson presentation, learning outcomes, student engagement, ease of navigation, and other factors (p. 198).

In the particular educational VR lab environment, the students identified some "bugs" in the software. Another finding: "Students identified two major areas which reduces (sic) the realism and immersion in the VR laboratory. The first item was the lack of a fluid and immersive experience mediated through a responsive computer interface. The second was lack of realism and the VR laboratory missing things found in a normal laboratory" such as a microscope and a balance (Lamb, 2020, pp. 199 - 200). Users also expressed an interest in tactual feedback. Some learning content was not found to link to the assessment (p. 201).

Pedagogically, the VR lab environment was missing "feedback and successive skill development in the VR environment (p. 204), which suggests the importance of pedagogical design for future iterations of the software. There were problems identified in installing the software for students, and teachers had issues with the software costs. Ultimately, there was a consensus result that the VR lab will not replace real-life wet labs. It is still not clear how effectively the learning transfers from the virtual to the real (p. 203), but there is general agreement of the criticality of "interaction, immersion, and authenticity" in educational environments for helping learners develop complex concepts (p. 205).

Educational virtual reality is in its infancy (Lamb, 2020, p. 192), and there are high hopes for its potential (even though we are well past the heyday of the initial rollout of such capabilities).

Laptop Workspace (by umeridrisi on Pixabay)

Details

Figure 6: Laptop Workspace (by umeridrisi on Pixabay)

In the Nexus between Math and Other Disciplines: Applied Interdisciplinary Math

Floriano Viseu and Helena Rocha's "Interdisciplinary Technological Approaches from a Mathematics Education Point of View" (Ch. 11) highlights the importance of artful teaching in order to optimally integrate math with various disciplines. Math has practical everyday applications, and it is used to virtually all fields. It is by nature interdisciplinary, multidisciplinary, and transdisciplinary. The coauthors write:

> According to Drake (1991), integration can be regarded in three ways: multidisciplinary, interdisciplinary, and transdisciplinary. And Williams et al. (2016) clarify the difference between these types of integration. We can speak of a multidisciplinary approach when mathematics is part of another curriculum subject, or when another subject appears in the mathematics classroom work. We have an interdisciplinary approach when two or more disciplinary contents are considered at the same time. This means that we are considering mathematics and some other(s) contents(s) simultaneously, while addressing a specific topic or theme, but in such a way that all the disciplines keep their specific nature. And we can speak of a transdisciplinary approach when 'the emphasis is less on bringing subjects together and more on the particular problem or project' that is the basis for the classroom work (Williams et al., 2016, 19). (Viseu & Rocha, 2020, p. 211)

And there is often overlap in the above approaches. In this work, the researchers focus on "tasks that promote interdisciplinary technological approaches from a mathematical point of view" (p. 210). They showcase three cases: about HIV (human immunodeficiency virus) infection rates in Portugal from 1983 to 2019 (pp. 217 – 219) which integrates math (data modeling, formulas of viral spread, visual graphing) and biology; about the movement of an object (pp. 220 – 222) which integrates graphing points-in-time measurements, schematics, and formulas; and about how gas pressure in an airtight syringe will vary with pressing the plunger (p. 223) which integrates mathematical modeling. This work shows the high demands on teachers to have various combinations of pedagogical content knowledge across disciplines.

Ethical STEM-ing to Opportunities and Challenges

Linda Hobbs' "STEM: Opportunities and Challenges for Education" (Ch. 12) focuses on four themes: "STEM definitions, STEM as practices, STEM as membership, and STEM as curriculum innovation" (p. 233). STEM collectively refers to Science, Technology, Engineering and Mathematics. These are seen as a linchpin of knowledge required for survival and thriving in the 21st century. In an educational setting, STEM is "a vehicle for powerful, equitable and sustainable education" (p. 233), to harness the full power of a population. STEM

learning may inform the required knowledge, skills, and attitudes (some say "abilities") or "KSAs" for the future workforces.

Various national-level governments have taken on advocating for STEM and mandating its inclusion in the required curriculum. Different countries are in different states of advancement of supporting STEM:

> In Australia, the Australian Curriculum, which is translated into state mandated curriculum, has no specific subject called STEM but teachers are supported through online materials and training to draw from the traditional subjects to make links between the STEM-related content and skills. New South Wales is the only state in Australia that has STEM as a curriculum area. The National STEM School Education Strategy (Education Council 2016), which is endorsed by the Australian government education ministry, sets the tone for Australia's approach to STEM. In comparison, Taiwan has no STEM curriculum or specific support materials for teachers, and STEM is discussed in relation to the individual STEM-related subjects rather than as an integrated approach to STEM (Gao 2014) (Hobbs, 2020, p. 234).

There are tradeoffs with government mandating and support, including competition for funding and political strife. Certainly, such leadership also means the setting of measurable standards. In many cases, there is funding for teacher professional development to enable the building of local in-school and in-classroom capacities. Some important STEM skills were identified in a vehicle design challenge; these include "flexible reasoning skills," "adaptable use of disciplinary practices and knowledge" such as conceptual and design tools, the ability to engage in "disciplinary language," and understanding evidence (Hobbs, Cripps, Clark, & Plant, 2018b, as cited in Hobbs, 2020, p. 241). STEM evokes different brand memberships, curricular innovations, technological sophistication, interdisciplinary collaboration, and other themes, in this work, which provides brilliant analysis of the current research literature around STEM education. Ultimately, Hobbs worries about the threat of STEM-fatigue with so many conferences and publications focused on this approach and as a "two-edged sword" (p. 249).

Integrating STEM in National Curricula: A Comparison and Contrast

Gráinne Walshe, Jennifer Johnston, and Merrilyn Goos' "Promoting 21st Century Skills through STEM Integration: A Comparative Analysis of National Curricula" (Ch. 13) focuses on interdisciplinary STEM teaching and learning frameworks (with math forefronted) in Australia, Ireland, and Scotland, and in particular, their lower secondary school curricula, as seen through a comparative analysis of curricular documents. The coauthors observe: "The broad trend in international curricular policy has been a move away from content-focused specifications towards increased emphasis on the development of students' competencies" (p. 255). In this qualitative cross-case document analysis, the research team focused on the overarching curricular purpose, curricular content, and instruction-related curriculum aspects (p. 260). This methodical work begins with a summary of each context for each country and then introduces the findings for each country. Then follows a comparative discussion.

One finding: The Scottish curriculum had "an initially strong emphasis on skills over content specification" and has evolved to focus more on "a narrower base of subject-specific skills, more closely related to traditional learning within a subject" (p. 268). Another observation: "On balance the Irish STEM education policy is more concerned with inculcating a broader range of 21st century skills in the students, while the Scottish and Australian policies are more focused on STEM education as a means to economic development, albeit with mention of students being inspired and enthused to learn in the STEM disciplines. It is not clear that the study of either mathematics or science will benefit by being tied to an economic rationales." (p. 268) In terms of ethical focuses, none of the national documents focused on "individual and environmental wellbeing, sustainability, or ethical awareness" (Walshe, Johnson, & Goos, 2020, p. 268). This work is highly relevant and readable, and the research methods are interesting.

Engaging the Heads, Hands and Hearts of Students for Better Futures

Alongside the better-known STEM is another construct known as STSE or "Science-Technology-Society-Environment." Liliane Dionne, Natascia Petringa, and Angela Fitzgerald's "Effective Teaching in Primary Science, Technology, Society and the Environment" (Ch. 14) engages this latter concept related to reaching "the head, hands and hearts of their students" (p. 275) in a more holistic sense of learners. They conduct research among practicing teachers to capture what works. Their model is built around the social construction of knowledge through various activities and intercommunications, based on the social-constructivist triadic pedagogical model which they adapted from Waldrip, Prain, & Carolan 2010, as cited in Dionne, Petringa, & Fitzgerald, 2020, p. 285).

They explain the three parts of reaching the head, hands, and hearts as including various elements. For the head-brain component, this team points to "questioning…at the root of the scientific activity" by asking sound questions, sharing ideas, following a plan and problematization issues, and being able to assess information and self-performance, among others (p. 282). Having multiple representations of science phenomena enables broader approaches to the learning. The "hands" part refers to the "sensorimotor dimension of the learning experience" for active learning (p. 281). They write about engaging the heart:

> First, connecting and engaging the heart requires stimulating content. This criterion for an effective practice helps to maintain student interest during a science activity and leads to student engagement. Linking classroom activities with students' day-to-day lives and relating activities to topics that interest this young generation are essential prerequisites for developing a sound learning process… Also linked to the students' heart is the second criterion, which corresponds to the connection with the community or the surrounding environment of school… In addition, often parents or other members of the community or the environment itself can be brought in to enrich the science activity, which in turn engages students on a deeper level. (Dionne, Petringa, & Fitzgerald, 2020, p. 281)

They add two criteria for successful teaching: "multimodal representations and community links" (p. 275). The multimodal representations include "teacher representation, student representation" and "multimodality: reading, writing, speaking, listening, doing, representing and interpreting" (p. 285). These richer approaches enable active engagement of the learning. Community links are important for action-oriented science or "citizen science" requires broader engagement beyond the school (p. 283). They enable richer practices given the many demands on teachers already and their scarcity in various schools. This chapter includes evocative case examples around physics, astronomy, the phenomenon of day and night, environmental education, and others, in this participatory research project.

Math in "Inclusive, Plurilingual, and Multicultural" Schools in Brazil

Solange H.A.A. Fernandes and Lulu Healy's "Mathematics Education in Inclusive, Plurilingual and Multicultural Schools" (Ch. 15) begins with a premise of a "borderless" and intercultural society (p. 297) and asks how to design mathematics learning to be more inclusive of diverse learners. This work forefronts social cultures and the importance of language and different embodied (situated) ways of experiencing the world for inclusive math education in Brazil. Here, they consider what math may be like for those using primarily sign languages or indigenous languages. Through collaborative design of scenarios for math learning, the coauthors have found that "moving towards an inclusive mathematics education necessitates the identification of how different resources lead to different learning paths" (p. 297). They explain:

> We do not follow the design paradigm that seems to characterize the way mathematics curricula are currently developed—that is, by beginning the design process with a view of normal or typical student in mind and only later attending to accommodations for students who do not fit this view. Our view is that such an approach positions difference as the problem, pathologizing the bodies of certain groups of learners, instead of the educational structures they are subject to" (p. 302).

Their focus is to validate various embodiments and to "expand pedagogic possibilities (p. 302). What follows are various creative assignments engaging learning about pyramids through student drawing, gesturing, historicity (as points of comparison), and social performances. They engage various devices, such as MusiCALcolorida, a multisensory tool for the expression of numbers and some calculations (pp. 307 - 308). Here numbers have a color component and patterned visual expression as well as sound (p. 309). A digital xylophone app (on smartphones) is integrated in another performance-based math assignment (p. 310). In some cases, students took the lead to design the co-learning. Still, the coauthors lament that school math tends towards "manipulations of abstract symbols on paper" and the so-called "hegemony of the symbolic" (p. 312) instead of the broader approaches. It is not yet clear if actual math learning is occurring with the more creative approaches, however, with the complex hyper-precision and logical processes. And do these less traditional approaches bring non-mainline learners closer into the fold, or does it leave them outside further and disenfranchise them further?

Accessible Hands-on STEM Labs for Everyone

Hands-on science labs are an important part of science learning, especially in anticipation of the Fourth Industrial Revolution (4IR). (Some suggest we are already in 4IR.) Yet, many teachers, because of concerns for laboratory safety, do not enable access to "students with disability/disabilities" (SWD). How can teachers better

judge the capabilities of SWD and lower barriers to access and ensure more equitability in learning? Cary Supalo and Jasodhara Bhattacharya's "Hands-On STEM Activities for Students with Disabilities" (Ch. 16) proposes more accessible classrooms (and lab spaces), and multi-sensory approaches, to enhance scientific observation and data analysis. Various adaptations have been made to enable more accessible science labs. In low resource environments, household goods are sometimes used in lieu of more expensive lab materials. Various adaptations have been made to enable similar lab learning for those with sight challenges (p. 323).

The coauthors identify various stakeholders (or "key actors") with interests in and effects on STEM labs (pp. 324-325). They then share ideas about ways to deal with barriers, while noting that safety cannot be compromised, and learners should not be expected to act beyond capabilities. How lab groups are constructed is also important to encourage socializing among all and intercommunications and collaborations. How laboratory instructions are given also matters; these should be "accessible" and "high-quality," including the use of Braille and large-print signage and "space for a service animal" out of the flow of human traffic (p. 327). Three-dimensional objects may be part of the learning to help SWDs and all students conceptualize particular objects and phenomena (p. 328). There are benefits to having all students engage in scientific experiments. The coauthors advocate using both low and high assistive technology interventions to help learners with single or various disabilities. One example they use is a device that conveys data in audio sonification (p. 329). Various science simulations may enable the experiential part of science labs without the direct physical requirements for lab space and direct in-person engagements (p. 330). Finally, the researchers here suggest the importance of having appropriate (and high) expectations for learners, SWD and others, given the high importance of teacher expectations (p. 331).

Portuguese Sign Language among Hearing-Impaired Learners in Mathematics Classes

For students with hearing impediments and low fluency in Portuguese, how are they to more effectively learn math when mathematical terms do not have an equivalent expression in Portuguese Sign Language (PSL) gestures? And given the social importance of intercommunications and the social isolation that can result from deafness, how can those with hearing disabilities not be disenfranchised further when it comes to learning? This is one of the challenges depicted in Joana Tinoco, Maria Helena Martinho, and Anabela Cruz-Santos' "Challenges Faced by Students with Hearing Impairment who use Portuguese Sign Language in Mathematics Classes" (Ch. 17), as a real-world case among two 6th grade students in an inclusive school. The coauthors offer a sense of background. For hearing impaired children, they often have parents who are not themselves very fluent in sign language. The children themselves often have poor mastery of the official language of the country, in both spoken and written forms of the language.

For this study, the work follows an 11-year-old girl who was diagnosed with profound deafness at 26 months (a prelingual stage). She wears bilateral prostheses and engages in her math class through simultaneous translation by a PSL interpreter. The other research participant is a 12-year-old boy who "depends entirely on sign language or mimes" (Tinoco, Martinho, & Cruz-Santos, 2020, p. 342). His parents decided against a cochlear implant for him when he was diagnosed deaf at age 3 (though he was born deaf). He communicates with his family through miming. What follows are intense descriptions of in-class observations. In one case, the PSL translator inadvertently gives away an answer in the translation. The respective works include oral dialogue sequences from the in-class work.

In another case, the coauthors write:

> Daniel had serious problems in reading PL and managing the meaning of words associated to everyday situations, such as produce, left over, check, market, reality, promotion or odd. For example, he was unaware of the meaning of checking, a word for which there is no gesture in PSL. If it had not been detected and explained by the PSL interpreter and the teacher, Daniel would not have been able to solve the proposed task, which asked to sort fractions using the major and minor symbols, because he simply did not know the meaning of what was being asked. (Tinoco, Martinho, & Cruz-Santos, 2020, p. 345)

The respective examples would resonate powerfully with math teachers who have likely experienced some similar experiences. This work shows the dependencies for learning, with so much dependent on clear communications and the deployment of language in its many forms (oral, written, gestural, and others). And in the particular learning domain, language uses are enriched in yet other ways.

Another takeaway from continuing observations of the students over several months:

> Although they attended an inclusive school that is a reference for hearing loss, with adequate human and material resources (for example, the presence of an interpreter in all classes), several communication difficulties remain. Actually, students with HI (hearing impairment) have to be considered as individuals that possess their own language and their own ways of appropriating and construct(ing) knowledge. Language has a major influence in the interpretation of the tasks proposed in the classroom. To succeed in these classes, and to be included, students must understand what is the meaning of what is being taught. They must be able to discuss the contents in order to interpret correctly. But to do so they need to understand PL in the written form and PSL. Otherwise the translations will often introduce misunderstandings or erode the precise meaning of the problem statement (Tinoco, Martinho, & Cruz-Santos, 2020, p. 349).

This work is an insightful one and advocates powerfully for the two subjects and others with similar learning needs.

Applying 21st Century Assessment to Math Ed

Farzad Radmehr and Pauline Vos' "Issues and Challenges of 21st Century Assessment in Mathematics Education" (Ch. 18) opens with the sense that mathematics assessments focused on "knowledge with low cognitive demands" and advocates for assessments requiring higher order thinking (HOT) for the 21st century along with teaching to that HOT.

This research team harnesses the revised Bloom's Taxonomy as a framework to focus on HOT: including lower-order to higher-order thinking "summarizing, comparing, explaining, exploring, analyzing, critiquing, and creating" (Radmehr & Vos, 2020, p. 359). One way to bring creativity to the forefront is to assign "problem-posing activities" described as the construction of "personal interpretations of concrete situations" as mathematical problems (Stoyanova & Ellerton, 1996, p. 1, as cited in Radmehr & Vos, 2020, p. 363). The coauthors share various examples of different problem posing tasks with different levels of cognitive demands. Another approach involves "puzzle-problems" that have four factors: "*simplicity, generality, entertainment*, and having an *eureka* factor" (Michalewicz & Michalewicz, 2008, as cited in Radmehr & Vos, 2020, 365. Such problems require deeper levels of reflection and analysis to solve. They also propose mathematical modeling as another option (p. 368), with tasks requiring logic and extrapolation. They describe the uses of the debriefing "Cloze Paragraph" after mathematical problem-solving to encourage more reflection and analysis of the prior work (pp. 371-372).

The ideas for enriched learning of math sometimes read like work for gifted learners. However, these may be possible with sufficient scaffolding and supports for all learners, if these are designed well and to the level of learner capabilities (in their zone of proximal development).

Rethinking Assessment

Finally, Jon Scaife's "Assessment for Learning" (Ch. 19) focuses on both "formative assessment" and "diagnostic assessment" ("a constitutive part of many professional and interpersonal processes") (p. 381) as methods that can be harnessed to improve student learning (generally speaking). This work cited Dweck's "fixed" and "growth" mindsets (2006) research to emphasize the importance of emphasizing the human capability for growth based on effort, in the context of properly constructed learning. This work updates some of the research in assessment, for purposive harnessing by teachers and learners, so feedback is constructive and not harmful. The author also shares some of his own teaching experiences and what he learned about eliciting answers from his students by bouncing around a class in a more inclusive way. He talks about framing story problems to a third party so as not to be threatening: "Imagine you have a younger sister and her class has been looking at how plants grow. If she said to you 'Do plants need sunlight?' what would you say to her?" (p. 392) He shares some clicker approaches to learning. Then he explores diagnostic teaching so as to make informed decisions about how to teach more effectively. He ends with the observations that it helps to tap into the core animating beliefs and values of learners and use that as the starting point of the learning instead of imposing a worldview (p. 396).

Conclusion

Science and Mathematics Education for 21st Century Citizens: Challenges and Ways Forward (2020) introduces programs (global, national, and local) that may help move humanity forward to meeting the challenges of the near-future, which is fast approaching. Humanity will need people with solid science rigor in all dimensions; they will need people who are creative, collaborative, conscientious and woke.

The coeditors hail from several universities: Laurinda Leite from the University of Minho, Portugal; Elizabeth Oldham from Trinity College Dublin, Ireland; Ana S. Afonso from University of Minho, Portugal; Floriano Viseu from the University of Minho, Portugal; Luis Dourado from the University of Minho, Portugal; and Maria Helena Martinho from the University of Minho, Portugal.

About the Author

Shalin Hai-Jew works as an instructional designer / researcher at Kansas State University. Her email is shalin@ksu.edu.

Thanks to Nova Science Publishers for graciously providing a review copy.

Comment on this page

Previous page on path Cover, page 1 of 3 Next page on path

scientific literacy 21st century makerspace Fourth Industrial Revolution (4IR) sustainability curriculum interdisciplinary math STEM inclusive science coding teacher professional development educational robotics virtual lab science-technology-society-environment (STSE) science education math education

Related: (No related content)