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2. FOUNDATIONS OF SCIENTIFIC, MATHEMATICAL, AND TECHNOLOGICAL LITERACIES—COMMON THEMES AND THEORETICAL FRAMEWORKS

The Pacific CRYSTAL Centre for Scientific and Technological Literacy was proposed knowing that many people in the academic and educational communities did not have or share common definitions of scientific literacy and mathematical literacy (also known as numeracy) and that the efforts to define and share technological, computer science, and engineering literacies were much more limited. However, Pacific CRYSTAL was designed on an interdisciplinary foundation involving (a) formal and informal environments for learning about science, mathematics, and technology; (b) scientists and engineers from these academic disciplines; and (c) educational researchers from counselling psychology, environmental education, indigenous studies, language and literacy, mathematics education, science education, and technology education. This broad involvement allowed Pacific CRYSTAL to adopt cognitive sciences (i.e., linguistic, pedagogical, ontological, epistemological, psychological, sociocultural) and constructivist perspectives for science, mathematics, and technology (SMT) literacies because these views were demonstrated to be part of contemporary educational reforms and practices (Ford, Yore, & Anthony, 1997). Surprisingly, there was very little collaboration amongst SMT educators in developing current reforms.

Technological literacy (International Technology Education Association [ITEA], 1996, 2003, 2006, 2007) and engineering literacy (United States National Academy of Engineering [NAE], 2010) standards have much shorter histories than the 50+ year history of scientific literacy and 20+ year history of mathematics literacy. In fact, “[the] ‘E’ in STEM [Science, Technology, Engineering, and Mathematics] has been silent” (NAE, p. vii) in USA education and totally missing in most of Canadian education; while the ‘T’ was associated with industrial or manual arts in both countries. There are some indications that the fragmented technology and engineering education is becoming consolidated in the USA with the recent (November 2010) name change of the major technology education association from the International Technology Education Association to the International Technology and Engineering Education Association (ITEEA); however, computer science education has not made a major impact in K–12 education.

Prior to the outset of Pacific CRYSTAL, much consideration had been given to scientific literacy (Ford et al., 1997; Hand, Prain, & Yore, 2001; Norris & Phillips,

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2003; Yore, Bisanz, & Hand, 2003) that proposed a framework for literacy in the discipline and understanding the big ideas of the discipline, which promote fuller engagement with socioscientific issues. Early efforts in CRYSTAL projects addressed the need to articulate a similar definition of mathematics literacy. However, similar efforts were not apparent for technology literacy, which in part may be due to the definitions of technology being reasonably narrow or confused with computational tools, engineering being confused as simply applied science, and computer science being strongly attached to computer hardware.

Current definitions of technology and engineering are defined as design under constraints—with nature being the fundamental constraint—and "time, money, available materials, ergonomics, environmental regulations, manufacturability, reparability and political considerations" being others (NAE, 2010, p. 6). Computer science has been a new arrival in many engineering and technology departments, sometimes transferring from faculties of mathematics and sciences where its defining characteristics were not fully embraced. Computer science, technology, and engineering involve iterative design or problem-solving processes that begin "with the identification of a problem and [end] with a solution that takes into account the identified constraints and [meets] specifications for desired performance … [and] do not have single, correct solutions[; technology, computer science, and engineering], by necessity, [are] creative [endeavours]" (NAE, pp. 6–7).

Therefore in this chapter, the development of a technological literacy framework, which includes engineering and computer science and parallels scientific and mathematics literacy, will be stressed. Technology is taken as a broad discipline spanning a continuum of inventors, technicians, technologists, professional engineers, and researchers. It is important to note that scientific, mathematical, and technological practices and literacies are distinct (scientific literacy—nature of the world; mathematical literacy—patterns and relationships of quantity, order, and shape; technological literacy—needs, problems, designs). However, many common features have been identified, such as "the use of mathematics, the interplay of creativity and logic, eagerness to be original," in both science and technology (American Association for the Advancement of Science [AAAS], 1990, ch. 3, p. 2). "It is the union of science, mathematics, and technology that forms the [technoscientific] endeavor and that makes it so successful. Although each of these human enterprises has a character and history of its own, each is dependent on and reinforces the others" (AAAS, 1990, ch. 1, p. 1). Furthermore, engineering and computer sciences are frequently viewed as partially overlapping with technology or as part of the technological continuum and that the crowded school program and curriculum mitigate against the development of another stand-alone curricular entry (NAE, 2010).

SCIENCE, MATHEMATICS, AND TECHNOLOGY LITERACIES

Participants in Pacific CRYSTAL generally agreed that science, mathematics, and technology (including engineering and computer science) are disciplines with unique but interconnected and related attributes and supported the idea that general (mainstream) SMT literacies ultimately resulted in fuller participation in the public debate about science, technology, society, and environment (STSE) issues leading to informed decisions and sustainable solutions and actions. Although general literacy focuses on mainstream citizenship, it also serves as a platform or springboard for elite (pipeline) literacy, leading to further academic studies and SMT-oriented careers and professions. It was the sincere belief of most participating investigators in Pacific CRYSTAL that greater attention to the fundamental literacy, disciplinary understanding, and socioscientific applications of the mainstream focus would alleviate much of the pipeline problems for underserved and underrepresented peoples entering higher studies and careers in these disciplines.

Science is generally characterized as inquiry, mathematics as problem solving, and technology as design—but all involve argumentation consisting of logical reasoning about knowledge claims, problem solutions and innovations based on empirical evidence, established procedures, or theoretical assumptions and foundations. Collaboration among CRYSTAL Alberta, Pacific CRYSTAL, and the National Science Council of Taiwan focused on constructing theoretical and empirical foundations for scientific and mathematical literacies. These efforts resulted in frameworks that provided fine structure and research basis for scientific and mathematical literacies building on earlier analyses of the US mathematics (United States National Council of Teachers of Mathematics [NCTM], 2000) and science (AAAS, 1990, 1993; United States National Research Council [NRC], 1996) reform documents that demonstrated focus on disciplinary literacies involving conceptual understanding of big ideas, critical thinking, and communications (Yore, Pimm, & Tuan, 2007) and support for associations (0.78–0.88) and shared variances (61–77%) amongst student Programme for International Student Assessment (PISA) performance in reading, mathematics, and science literacies not reported elsewhere (Anderson, Chiu, & Yore, 2010). PISA used noncurricular definitions of these literacies, which have morphed somewhat over the 2000–2006 period; but they have retained focus on adult needs, real-world applications, and informational text (Table 1).

The following sections summarize key attributes of SMT literacies that use a common framework to promote public engagement with STSE issues. Each literacy will be defined and illustrated using common interacting senses of fundamental literacy in the discipline and derived understanding of the discipline—science, mathematics, or technology. A cautionary note must be considered here in that many standards are presented as learning progressions for primary, middle, and secondary schools; they are based on experts' hypotheses and not empirical research results.

Scientific Literacy

Science Literacy for All is a long promoted, but ill-defined general expectation (Hurd, 1958) with international cache (McEneaney, 2003), which runs the risk of being cast off as an outdated slogan, logo, or rally flag rather than an essential framework to guide science education (Yore, 2009). Science Literacy for All does not

Table 1. PISA definitions of mathematics, science, and reading literacy (OECD 2000, 2003, & 2006 from Anderson et al., 2010, pp. 376–377)

Year	*Mathematics*	*Science*	*Reading*
2000	The capacity to identify, to understand, and to engage in mathematics and make well-founded judgments about the role that mathematics plays, as needed for an individual's current and future private life, occupational life, social life with peers and relatives, and life as a constructive, concerned, and reflective citizen.	The capacity to use scientific knowledge, to identify questions, and to draw evidence-based conclusions in order to understand and help make decisions about the natural world and the changes made to it through human activity.	Understanding, using, and reflecting on written texts in order to achieve one's goals, to develop one's knowledge and potential, and to participate in society.
2003	An individual's capacity to identify and understand the role that mathematics plays in the world, to make well-founded judgments, and to use and engage with mathematics in ways that meet the needs of that individual's life as a constructive, concerned, and reflective citizen.	The capacity to use scientific knowledge, to identify questions, and to draw evidence-based conclusions in order to understand and help make decisions about the natural world and the changes made to it through human activity.	An individual's capacity to understand, use, and reflect on written texts in order to achieve one's goals, to develop one's knowledge and potential, and to participate in society.
2006	An individual's capacity to identify and understand the role that mathematics plays in the world, to make well-founded judgments, and to use and engage with mathematics in ways that meet the needs of that individual's life as a constructive, concerned, and reflective citizen.	An individual's scientific knowledge and use of that knowledge to identify questions, to acquire new knowledge, to explain scientific phenomena, and to draw evidence-based conclusions about science-related issues, understanding of the characteristic features of science as a form of human knowledge and enquiry, awareness of how science and technology shape our material, intellectual, and cultural environments, and willingness to engage in science-related issues, and with the ideas of science, as a reflective citizen.	An individual's capacity to understand, use, and reflect on written texts in order to achieve one's goals, to develop one's knowledge and potential, and to participate in society.

assume or preclude elite-level studies and science-related careers (pipeline interpretation); rather, it embraces practical, civic, and cultural aspects (mainstream interpretation; Shen, 1975). Roberts (2007) classified definitions of science literacy as emphasizing science understanding (Vision I) or contextual applications (Vision II). Analyses of science education reforms (Ford et al., 1997; Hand et al., 2001) and the theoretical construct (Norris & Phillips, 2003) identified interacting fundamental and derived senses of science literacy. The fundamental sense subsumes abilities, emotional dispositions, and information communication technologies (ICT) as well as language (speaking–listening, writing–reading, representing–interpreting) and mathematics. The derived sense subsumes the content goals regarding understanding the big ideas of science (nature of science, scientific inquiry, technological design, and the relationships amongst STSE). These fundamental and derived senses of science literacy lead to fuller and informed participation in the public debate about STSE issues (Vision III). Table 2 illustrates the two interacting senses, components, and cognitive symbiosis between the senses and amongst the components within both senses. For example, peoples' views of science will influence their use of scientific metalanguage (theory, proof, certainty, etc.), and their prior conceptual knowledge about the domain and topic will influence their reading comprehension of texts focused on the domain or topic. People's understanding of science will influence their inquiries and explanations of the resulting data and their critical thinking will influence their choice and interpretation of information accessed from the Internet.

Table 2. Interacting senses of scientific literacy—Cognitive symbiosis (Yore et al., 2007, p. 568)

Fundamental sense	*Derived sense*
Cognitive and Metacognitive Abilities	Understanding the Big Ideas and Unifying Concepts of Science
Critical Thinking/Plausible Reasoning	Nature of Science
Habits of Mind	Scientific Inquiry
Scientific Language (including mathematical language)	Technological Design
Information Communication Technologies (ICT)	Relationships among Science, Technology, Society, and Environment (STSE)

Fundamental sense of scientific literacy. The fundamental sense of being literate in a discipline is somewhat more contested and less well documented (Moje, 2008; Shanahan & Shanahan, 2008), but it involves more than the ability to talk and read science. The contents of this sense encompass the cognitive, affective, psychomotor, and linguistic requirements of constructivist models of learning as making meaning rather than taking meaning. The *cognitive and metacognitive* (awareness—declarative, procedural, and conditional knowledge; and executive control of cognition—planning, monitoring, and regulating) abilities and strategies include a variety of knowledge building and science processes, argumentation, and planning and evaluating procedures. *Critical thinking/plausible reasoning* is about deciding what to believe or do about a challenge and the abductive, inductive, deductive, and hypothetico-deductive logics used in scientific reasoning. *Habits of mind* involve emotional dispositions (beliefs, values, attitudes, and critical-response skills) toward science and scientific inquiry (AAAS, 1993). *Scientific language* involves the use of metalanguage, words, symbols, numbers, and representations to develop procedures, build arguments, construct knowledge claims, and communicate these processes, arguments, and claims to others. Language, both natural and mathematical, shapes what is known as well as reports what is known and persuades others about these ideas. Most interpretations of the roles of language in science overemphasize the importance of mathematical language and the communicative role of language—while overlooking the constructive (language as cognitive technology/tool) and persuasive (argument) aspects in constructing understandings. Talking–listening about science with peers and with the teacher provides students with opportunities to make sense of their thinking, hear others' ideas, become aware of multiple perspectives, rethink ideas, evaluate others' ideas, and frame their ideas.

Unfortunately, K–12 teachers dominate classroom discussions and do the majority of talking. Therefore, students do not spend sufficient time producing language and interacting with others in exploratory talk, which allows them to process both language and content more deeply and to negotiate meaning and adjust their language to make it comprehensible to their audience. Writing–reading about ideas within an inquiry science context creates opportunities to propose claims, reinforce arguments, and revise conceptual knowledge and models for different modes of text, thereby building structures necessary for reading informational texts. Representing–interpreting various modes of text (print, numerical, graphic, etc.) influences depth of processing and understanding in science (Yore & Hand, 2010). Scientific-literate people construct and use multiple representations (including sketches, diagrams, models, tables, charts, maps, pictures, graphs); use visual and textual displays to reveal relationships; locate and evaluate information from various textual and digital sources; and choose and use appropriate vocabulary, spatial displays, numerical operations, and statistics. Scientists do science with and are limited by available technologies and use *ICT* to cooperate; coauthor; share databases; display, analyze, and model data; and construct new knowledge. Scientific-literate students use similar ICT to troubleshoot, solve problems; access, process, manage, interpret and communicate information; and create representations (Partnership for 21st Century Skills, 2004a).

Derived sense of scientific literacy. The derived sense of scientific literacy is reasonably well understood and accepted in the science education community and international science education reform documents (Yore, 2009). There is some disagreement on the specifics, but when taken at the general level, there is a reasonable consensus. The *big ideas and unifying concepts* consider the major content for biological, earth and space, and physical sciences that apply across domains and topics or provide a foundation for work in a specific domain. The *Pan-Canadian Framework of Science Learning Outcomes* (Council of Ministers of Education, Canada [CMEC], 1997) identified the following unifying concepts: constancy and change, energy, similarity and diversity, and system and interactions. The *nature of* *science* is frequently promoted as inquiry, but it could equally well be defined as argument. The specifics about the nature of science are contested; but there is reasonable agreement about science as people's attempt to systematically search out, describe, and explain generalized patterns of events in the natural world through observing, thinking, experimenting, and validating—also that the explanations stress natural physical causalities and cause-effect mechanisms, not supernatural, mystical, magical, or spiritual causes (Good, Shymansky, & Yore, 1999). However, traditional, modern, and postmodern interpretations vary significantly (Yore, Hand, & Florence, 2004) and cultural views differ from Western views (Yore, 2008). Attempts to engage diverse groups must be cautious of these differences to avoid misleading students about the nature of Western science. Respectfully, "Explanations about the natural world based on myths, personal beliefs, religious values, mystical inspiration, superstition, or authority may be personally useful and socially relevant, but they are not science" (NRC, 1996, p. 201). *Scientific inquiry* is a curiosity-driven, creative, dynamic, and recursive process while *technological design* is a mission-driven process seeking to adapt the environment to people's needs and to alleviate problems (ITEA, 2007). *STSE issues* (climate change; oil spills; fish farms; air, water, and land pollution; resource depletion; natural hazards, etc.) are major concerns currently facing people. These known and unknown issues are ultimate foci of and relevant contexts for scientific literacy.

Mathematical Literacy

Success in the 21st century society, world of work, and life involves mathematical understanding, quantitative reasoning, problem solving, modeling, visualizing, and making well-founded judgments and decisions (Organisation for Economic Co-operation and Development [OECD], 2003). Mathematical literacy is specifically used here to avoid numeracy, which is a contentious and contested term frequently focused on number sense and skills. Mathematical literacy is more than recalling basic facts, using memorized algorithms, and performing simple calculations; it involves understanding the mathematical enterprise and mathematics and the abilities, reasoning, emotional dispositions, language, and ICT to make sense of and solve quantitative problems.

Analyses of the Western and Northern Canadian Protocol (WNCP) for mathematics (WNCP for Collaboration in Education, 2006) and the USA's Principles and Standards for School Mathematics (NCTM, 2000) built on earlier analyses (Ford et al., 1997). The process and content standards were organized and supplemented to produce a framework for mathematical literacy that parallels scientific literacy and illustrates the interactions between and within the fundamental and derived senses (Table 3). People's knowledge about mathematics and problem solving interacts to help them find solutions for real-world problems and their emotional dispositions about certainty influence their thinking and reasoning. Furthermore, views about the nature of mathematics will influence the choice and use of mathematical terms and language since the metalanguage precisely represents the acceptable view of mathematics and common terms are used in uniquely mathematical ways.

Table 3. Interacting senses of mathematical literacy—Cognitive symbiosis (Yore et al., 2007, p. 577)

Fundamental sense	*Derived sense*
Cognitive and Metacognitive Abilities	Understanding the Big Ideas, Strands, and Substrands of Mathematics
Mathematical Thinking and Quantitative Reasoning	Nature of Mathematics
Habits of Mind	Knowledge about Problem Solving
Language of Mathematics (including proofs as arguments)	Real-world Problems
Information Communication Technologies (ICT)	

Fundamental sense of mathematical literacy. The WNCP (2006) process standards (communication, connections, mental mathematics and estimation, problem solving, reasoning, technology, visualization) provided foundations for defining the cognitive, metacognitive, reasoning, habits of mind, language, and ICT abilities comprising fundamental literacy in mathematics. These standards identified the *cognitive* processes for constructing, connecting, and integrating understandings into coherent systems and the *metacognition* required for being aware of what, how, when, and where to use these processes and for planning, monitoring, regulating, and reflecting on the operations involved in problem solving (NCTM, 2000). The process standard of reasoning and proof involves *critical thinking* about what to believe and what to do in mathematics: "Develop and evaluate mathematical arguments and proofs. … Select and use various types of reasoning and methods of proof." (NCTM, 2000, p. 402). *Habits of mind* toward doing mathematics and engaging the quantitative world includes beliefs, values, attitudes, and critical-response skills. "Teachers should consistently expect students to explain their ideas, to justify their solutions, and to persevere, … to expect and ask for justifications and explanations, [while realizing that] demonstrating respect for students' ideas does not imply … all ideas as reasonable or valid." (NCTM, 1991, pp. 57–58). Furthermore, students develop their mathematics self-efficacy, mathematics self-concept, and "confidence in their abilities to reason and justify their mathematical thinking" (WNCP, 2006, p. 8). Mathematics is a *sign system and distinctive discourse* that uses a variety of verbal languages, specific metalanguage, symbol systems, gestures, and representations that support the construction of understanding and communication of mathematics (NCTM, 2000). The communication and connections standards emphasize organizing and consolidating thinking; connecting diverse representations; analyzing and evaluating; and integrating, expressing, and reporting understandings. The representation standard involves selection, creation, translation, and applications of data displays, equations, models, and visuals to reveal patterns, interpret data, and transmit ideas. *ICT*, which should not be simply limited to computational tools, allow mathematicians, students, and users of mathematics to construct knowledge claims and understandings and apply mathematics, quantitative thinking, and statistical and data modelling techniques to create, compare, translate, and link multiple representations, to illustrate patterns and relationships, and to explain how components are connected and change (Partnership, 2004a).

Derived sense of mathematical literacy. The five NCTM (2000) *content standards* (number and operations, algebra, geometry, measurement, data analysis and probability) are regrouped and identified as four *strands/substrands*: number, pattern and relations (patterns, variables, equations), shape and space (measurement, 3-D objects and 2-D shapes, transformations), and statistics and probability (data analyses, chance, uncertainty) in the WNCP for mathematics (2006). The *nature of mathematics* as theoretical and applied disciplines attempt to search out, describe, and explain patterns and relationships of order, quantity, and shape amongst abstractions or real-world objects and events (AAAS, 1990). Mathematics and inherent processes are interwoven with science and technology and underpin actions in daily life, work, and culture (NCTM, 2000). *Problem solving* is a defining attribute of mathematics that involves identification of the problem, understanding influential factors and potential solutions, representing aspects of the problem space with abstractions, manipulating logically these abstractions according to established rules, and evaluating any resulting solutions or relationships against the problem conditions and mathematical assumptions and rules. Although mathematics is not bound by reality, relevance and *real-world problems* are central to applied mathematics and to making judgments about the real world and naturally occurring events.

Technological Literacy

The development of a parallel framework for technological literacy was necessitated by the inclusion of this goal in the Pacific CRYSTAL proposal, knowing that the construct was only partially articulated and implemented in K–12 schools in Canada. In British Columbia (BC) schools, this was apparent in the fragmented and unconnected curricular changes—informational skills involving ICT was changed from a stand-alone curriculum to integrated entries in the content areas (http://www.bced.gov.bc.ca/irp/te11_12/intro3.htm) and industrial arts and home economics to applied skills in automotive, construction, clothing, and food technologies (http://www.bced.gov.bc.ca/irp/welcome.php). The efforts to define technological literacy were made somewhat more difficult with the need to define technology with the broader context including computer science and engineering, to identify misconceptions about technology, and to differentiate between technology uses in science and mathematics as data collection and calculation aids and technology as way of solving problems.

Technological Literacy for All is “the ability to use, manage, and understand technology” (ITEA, 1996, p. 6), where (a) technology is defined as “human innovation in action” (p. 16), (b) engineering is “defined as design under constraint, … and the most fundamental of these constraints is the laws of nature … [while other] constraints include time, money, available materials, ergonomics, environmental regulations, manufacturability, reparability, and political considerations” (NAE, 2010, p. 6), and (c) computer science (or computing science) is defined as a field that studies information and computation. Computer science is often mistakenly linked to computers—the vacuum tube monsters of the 1960s, microelectronic versions of the 1970s, or today's PCs—when it is the study of computation and problems that includes a variety of disciplines devoted to computing and problem solving, such as algorithms, as well as the creating, organizing, displaying, and processing of information (see Carruthers et al., Chapter 6 this book). Computer science is in fact only secondarily connected to computers. Often, computer scientists are even asked to fix computers, which is comparable to asking a biologist to heal a person. Many of the fundamental computer-liberated conceptual aspects are clearly illustrated in *Computer Science Unplugged* (Bell, Witten, Fellows, Adams, & McKenzie, 2006).

Therefore, technology is taken here to represent a broad spectrum of studies and careers—inventor, technician, technologist, engineering assistant, computer programmer, professional engineer, computer scientist, and research engineer. The ITEA technological literacy rationale focuses on the "knowledge about the nature, behavior, power, and consequences of technology from a broad perspective" (1996, p. 1). The NAE (2002) stated, "[The] goal of technological literacy is to provide people with the tools to participate intelligently and thoughtfully in the world around them. … As people gain confidence in their ability to ask questions and think critically about technological developments [and STSE issues generally], they are likely to participate more in making decisions" (pp. 3–4)—the central goal of Pacific CRYSTAL.

Technology has a rich history that predates science, having changed from the practical arts domain of craftspeople and inventors using intuition, apprenticed skills, and trial-and-error procedures to large organizations of professional technologists and networks of engineering science required to engage in complex problems and develop interdependent technologies (NAE, 2002). Woollacott (2009) developed taxonomies of engineering competencies taken as intellectual capacities, knowledge, skills, abilities, attitudes, and other characteristics required for skilful performance that enriches society, empowers people, and enhances economic and social development, which could provide a keystone for defining K–12 technological literacy. These "inter-related processes, knowledge, skills and attributes involved in engineering a technical system or product from its conception, through design, construction and implementation, through its operation and eventual life-end and disposal" (p. 268) are very much context and function related with adaptive attributes identified to allow effective movement between specific problem and work spaces. Furthermore, he recognized the importance of language, especially written language reflective of audiences and genres and the basic principle of constructivist approaches, to assess what learners know and then to use this information to design and deliver appropriate instruction.

The vague understanding of and lack of familiarity with technology have led to misconceptions, such as "technology is merely the application of science [and technological determinism that posits] technological developments [are] largely independent of human influence" (NAE, 2002, p. 51).

> Most people have very few direct, hands-on connections to technology, except as finished consumer goods. … They are not aware that modern technology is the fruit of a complex interplay between many factors including science, engineering, politics, ethics and law. Another common misconception is that

> technology is either all good or all bad rather than what people and society make it. They misunderstand that the purpose for which we use a technology may be good or bad, but not the technology itself. (NAE, 2002, pp. 5–6)

Technology and engineering, like science and mathematics, are processes—*verbs*—"human innovation in action" (ITEA, 1996, p. 16) and "design under constraints" (NAE, 2010, p. 6). However, people perceive them to be *nouns*—emphasizing the products (e.g., computers, cell phones and other microelectronic devices, bridges, cars, space shuttles, skyscrapers but unlikely stone tools, wheels, levers, cups, etc.)!

Gallup polls commissioned by ITEA (Rose & Dugger, 2002; Rose, Gallup, Dugger, & Starkweather, 2004) revealed that adults in the USA were interested but not well informed about technology. Comparisons of the two polls (2001 & 2004) indicated that Americans' opinions and beliefs were reasonably stable, they recognized the importance of technology, they valued technological literacy and K–12 technology education, their beliefs were heavily influenced by personal environments and experiences and recent microelectronic inventions and do not reflect the long history of technology and the complex infrastructure supporting technological innovations, and they demonstrated some gender- and age-related differences. Younger respondents expressed interest in knowing how technology works and believed they had influence in decisions about technology-related issues and applications. There is no reason to assume that Canadians' opinions and beliefs differ drastically from those reported by these Americans. However, the rapid changes within technology and present STSE issues will likely have changed the specifics identified by North American respondents today.

The science education reforms (AAAS, 1990, 1993; NRC, 1996) provide numerous mentions and links to technology, engineering, and design; however, they "do not add up to a comprehensive portrayal of the role of engineering [and technology] in scientific activities" (NAE, 2010, p. 24). There is no well-accepted or shared definition of technology literacy that reflects contemporary constructivist learning and the constructive, persuasive, and communicative roles of language in doing and learning technology; as well, there appears to be little progress made in achieving goals based on any of the definitions available. The NAE (2002) suggested that technological literacy is a range of general to elite competencies involving broad and essential understandings of the people-built environment and their place in this designed world, which "encompasses three interdependent dimensions—knowledge, ways of thinking and acting, and capabilities" (p. 3).

Sneider (2010) provided a summary of the big ideas in engineering as knowledge (design, human culture, contrast of science and technology), habits of mind or ways of thinking and acting (systems thinking, desire to encourage and support effective teamwork, concern for societal and environmental impacts), and skills or capacities (designing under constraint, using tools and materials, mathematical reasoning). Knowledge, along the limited–extensive dimension, involved the recognition of technology's pervasiveness; understanding basic engineering concepts, the relationships amongst people's histories, influences, and technology, and technology reflecting the values and culture of society; and familiarity with the nature and limitations of the design process, anticipated and unanticipated risks, trade-offs, and cost-benefit balance. The ways of thinking and acting, along the poorly–highly developed dimension, involved asking pertinent questions regarding the benefits and risks of technologies, seeking information about new technologies, and participating appropriately in decisions about the development and use of technology. The capabilities, along the low–high dimension, involved a range of ICT skills, identifying and fixing simple mechanical or technological problems, and applying basic mathematical concepts related to probability, scale, and estimation to make informed judgments about technological risks and benefits.

Technology education is varied across and within countries. It has been developed as a requirement in the Czech Republic, France, Italy, Japan, The Netherlands, Taiwan, and the United Kingdom (NAE, 2002). Design is a central theme of some programs (Illinois State University Center for Mathematics, Science, and Technology [IMaST], n.d.) and specific modules in elementary and middle schools in the USA (Biological Sciences Curriculum Study [BSCS], *Teaching Relevant Activities for Concepts and Skills* [TRACS], 2000; Lawrence Hall of Science, University of California Berkeley, *Full Options Science System* [FOSS], 2003; National Science Resources Center, *Science and Technology Concepts* [STC], 2009). Technology education in Canadian schools has been modified over the years, with the traditional business education, home economics, and industrial arts being refocused into applied skills with a strong technology influence.

In BC, the K–7 information technologies and skills were integrated into the content area curricula (BC Ministry of Education [MoE], 1996) while middle schools offer Technology 8 (MoE, 1995). The K–7 curricula focused on a specific set of cognitive, affective, and motor skills related to operating a device, achieving a task, locating, organizing and managing information, and problem solving with information technologies; however, they did not fully embrace the inherent features of the nature of technology, designs to extend people's capacities, and problem solving. The Grade 8 curriculum more completely reflects technological design and problem solving with specific learning outcomes related to self and society (solve problems that arise during the design process, identify practical problems in various contexts, collaboration, etc.), communications (concept sketches and final drawing, use various information sources to solve problems, develop 2-D and 3-D representations manually and with the assistance of graphic technologies, etc.), production (describe and use product design process, consider, specific and select materials based on requirements and characteristics, safe work habits, identify ways to minimize waste, etc.), control (design and construct controls, compare ways controls work, etc.), and energy and power (select energy transmission and conversion systems, identify how simple machines are used, etc.).

Yore (2010) synthesized these documents to develop a preliminary framework for general technological literacy—parallel to mathematical and scientific literacies—that would more fully identify the formal and informal expectations of students leaving the K–12 system and would address some of the NAE (2010) recommendations (Table 4). He built on earlier work (Ford et al., 1997) and existing technology education (not to be confused with educational technology) curricula to illustrate the critical features of the technological design process and

Table 4. Interacting senses of technological literacy—Cognitive symbiosis (Yore, 2010)

Fundamental sense	*Derived sense*
Cognitive and Metacognitive Abilities	Understanding the Big Ideas and Core Concepts
Critical and Creative Thinking	Nature of Technology
Habits of Mind	Technological Design
Technological Language (including Mathematics)	Designed World
Information Communication Technologies (ICT)	Relationships among Science, Technology, Society and Environment (STSE)

the abilities to use and manage these innovations. The abilities to use contemporary technological systems involves "much more than just knowledge about computers and their application [while management] involves insurance that all technological activities are efficient and appropriate [and understanding involves the synthesis of] information into new insights" (ITEA, 1996, p. 6). Grade-level expectations (e.g., K–2, 3–5, 6–8, 9–12) for some of these dimensions are specified by the benchmarks (AAAS, 1993; ITEA, 2007), ICT Literacy Maps (Partnership, 2004b), instructional resources packages (MoE, 1995, 1996), and assessment guides (ITEA, 2003). Caution is needed here, since there is very limited empirical evidence to justify these theoretical learning progressions.

Fundamental sense of technological literacy. Fundamental literacy in technology involves abilities, thinking, habits of mind, language (natural and mathematical), and ICT that allow people to design, produce, select, use, evaluate, and manage technological enterprises and innovations. Much of the fundamental sense of technological literacy reflects the fundamental senses of mathematical and scientific literacies because of the close connections amongst the three disciplines.

Cognitive and metacognitive abilities Technology involves constructing understandings and creating designs to meet or alleviate needs, solve problems, and extend human capacities. Technologically literate people must develop and demonstrate the "abilities to apply the design process, … maintain technological products and systems, … [and] assess the impact of products and systems" (ITEA, 2007, p. 113). These abilities involve identifying needs and opportunities, finding solutions, enacting design procedures, and building new innovations and solutions for reasonable problems. The cognitive processes may involve (a) creative insights (gestalts); (b) applying existing knowledge or prior solutions within unfamiliar contexts, accepted standards, existing constraints, and current limitations; and (c) testing and evaluating these designs to inform redesigns as required. Metacognition here involves the declarative (what), procedural (how), and conditional (when, where) knowledge and the real-time self-management or executive control (planning, monitoring, regulating) required to successfully design, test, evaluate, and redesign solutions (Bybee, 2010).

Critical and creative thinking. Thinking critically and creatively (asking pertinent questions regarding risks and benefits, assessing impact and consequences, seeking information, brainstorming alternatives, making decisions, etc.) is central to technology (ITEA, 2007; NAE, 2002). Deciding what to do or believe about a pressing problem or persistent need requires analytical thinking to identify the problem or need, relevant information, factors and skills, potential solutions and appropriate tests. Creating and considering alternative solutions from various perspectives requires using established solutions and others from 'outside the box' that reflect the identified criteria and constraints. They use systems thinking and nonroutine problem solving to make decisions regarding the design and applications of technologies involving a spectrum of qualitative–quantitative plausible reasoning (abduction, induction, deduction, etc.) and rational argumentation.

Habits of mind. Successful design and problem solving involve habits of mind (ways of acting, emotional dispositions, processes, manual skills, beliefs, attitudes, etc.) toward the technological enterprise, doing technology rather than listing products, and design procedure to create new products, systems, and environments. Technologically literate people have a balanced perspective involving scepticism, certainty, trust, self-efficacy, optimism, and willingness to seek solutions and view technology ethically and thoughtfully, being neither categorically antagonistic nor uncritical (AAAS, 1993; ITEA, 2007; NAE, 2002, 2010). They exhibit social skills (collaboration and individualism), adaptability, and rely on basic (observing, measuring, inferring, forecasting, estimating, predicting, classifying, visualizing, modelling, etc.) and complex (identifying needs and problems and deciding whether to address them; specifying criteria, limitations, and constraints; planning and applying design procedures, evaluating alternative designs and solutions, etc.) processes. They develop their manual capacities and craft skills to fashion plans, produce innovations, and maintain and manage technologies; use hand tools, power equipment, and technologies properly and safely; and troubleshoot systems to identify malfunctions, solutions, and redesigns (AAAS, 1993).

Technological language. Technologically literate people use natural and mathematical language abilities and strategies to communicate their innovations and solutions to diverse audiences; record, justify, and explain procedures, operations, and results; negotiate and construct shared solutions amongst collaborators; report findings; and persuade others of the validity of these solutions, ideas, and understandings. Some language tasks and strategies such as negotiations, representations, and arguments (backings, warrants, evidence, claims, counterclaims, and rebuttals) serve communicative, persuasive, and constructive functions. Communicative and persuasive aspects involve but are not limited to (AAAS, 1993):

- judge and indicate reasonableness of forecasts, estimations, measurements, and calculations and identify sources of disparities;
- keep understandable notebook of procedures, data, and designs to address ethical and proprietary issues; and

- use appropriate metalanguage, logical connectives, and terminology to describe designs, systems and subsystems, and relationships, and develop and deliver compelling arguments about these ideas.

Constructive aspects of language are less well articulated, but current research in disciplinary literacies and systemic functional linguistics provide insights into how language helps constitute understandings and construe meaning. These aspects involve but are not limited to:

- recognize the value of and use the knowledge construction cycle involving speaking, writing, and representing—compose, review, feedback, and revise;
- use and transform sketches, scale drawings, blueprints, diagrams, maps, pictures, data tables, charts, models, and other representations in making claims, constructing understanding, and developing explanations; and
- manipulate symbolic representations using established mathematical rules that produce other statements with the same relationship to locate mutual solutions within the established limitations and constraints.

Information communication technologies. ICT have changed how engineers, technologists, and technologically literate people go about doing technology, designing and understanding innovations, and informing and persuading themselves and others about these ideas. ICT allow people to design, model, test, and refine innovations without actually building the product, to produce prototypes and products using computer-assisted design or 3-D printing, collaborate at a distance by moving ideas not people, and share large databases to facilitate each others' work. ICT abilities involve but are not limited to (AAAS, 1993; Partnership, 2004a):

- understand, manage, and create effective oral, written, and multimedia communications and representations;
- use computers and other technologies to design, represent, model, and display data, ideas, solutions, and innovations;
- collect, select, summarize, and analyze data and information from multiple sources; and
- produce clear and secure records, calls for proposals, designs, and testing procedures while anticipating the need to establish proprietary rights and patents.

Derived sense of technological literacy. Like mathematical and scientific literacies, technological literacy involves knowledge about the big ideas and unifying concepts (called *core concepts* by ITEA, 2007, and *core ideas* by NAE, 2010), the nature of the discipline, the defining characteristic—design, the worlds produced by these efforts, and the relationship within and amongst technologies, science, society, and the environment. There is reasonable general agreement on these dimensions, but there is some level of disagreement on specifics (ITEA, 2007; NAE, 2002). Custer, Daugherty, and Meyer (2010) systematically reviewed curricula, philosophies, and standards and then held focus groups and conducted Delphi studies to identify 14 common conceptual foundations of K–12 engineering education: 11 were revealed by all 5 inputs, 2 were revealed by 4 of the 5 inputs, and 1 was revealed by 3 of the 5 inputs.

Understanding the big ideas and core concepts. The core concepts in technology involve systems, resources, requirements, functionality, efficiency, optimization and trade off, processes, and controls (ITEA, 2007; NAE, 2010). Systems are building blocks for more complex systems and represent a way of thinking. Resources involve humans, materials, and technologies and their inherent qualities, availabilities, costs, and disposal risks. Requirements involve the criteria, physical laws, and constraints placed on a system, product, or setting. Optimization and trade-off are critical, on-going choices or exchanges in selecting resources, ranking requirements, designing and making products. Processes involve a "systematic sequence of actions used to combine resources to produce and output" innovations (ITEA, 2007, p. 33). Controls involve planned processes and evaluation–feedback loops to ensure that a product, service, or system meets established criteria and is performing as intended.

Nature of technology. Nature of technology cannot be fully captured as an applied science although it is associated with science and mathematics. Technology predates science, it is found in various cultures without well-defined science traditions, and it is replete with examples of innovations that preceded the scientific understanding of the related science (keystones, crystal radios, kites, herbal medicines, etc.). "Technology is the modification of the natural environments in order to satisfy perceived human needs and wants" by means of design (ITEA, 2007, p. 7) and "extends human potential by allowing people to do things they could not otherwise do" (p. 22). Technologically literate students understand "the characteristics and scope of technology … [and] relationships among technologies and the connections between technology and other fields of study" (p. 21). Sometimes, technology results in products with unintended outcomes and creates demands and opportunities for scientific and mathematical advances (AAAS, 1993).

Technological design. Design methodology is the defining attribute and core problem-solving strategy of technology; it differs from scientific inquiry in that the design cycle identifies a need or problem, proposes solutions, tests the solution to get evaluative feedback, and proposes redesigns, refinements, or further solutions based on the feedback. Technological design is mission-driven and recursive involving (ITEA, 2007):

> [A] number of well-developed methods for discovering such solutions, all of which share certain common traits. First, the designers set out to meet certain design criteria, in essence, what the design is supposed to do. Second, the designers must work under certain constraints, such as time, money, and resources. Finally, the procedures or steps of the design process are interactive and can be performed in different sequences, depending upon the details of the particular design problem. Once designers develop a solution, they test it to discover its shortcomings, and then redesign it—over and over again. (p. 90)

Intuition, brainstorming, prior solutions, practical experiences, and engineering science interact within the design process in which trial-and-error is still recognized as worthwhile in a few situations. Cost, human, and procedural considerations of production, operations, maintenance, replacement, disposition, marketing, and sales are part of designing innovative devices and processes (AAAS, 1993). Risk analysis is an essential part of design and must consider public perceptions of technological, scientific, and psychological factors as well as safety considerations. Reduction of failure is addressed with performance testing that involves simulations, small-scale prototypes, mathematical models, analogous systems, and part–whole variations (ITEA, 2007).

Designed world. Today's world is a combination of the natural and people-built worlds. People must select, use, and manage various technologies: medical, energy and power, information and communication, transportation, manufacturing, construction, and agricultural and related biotechnologies (ITEA, 2007). Social and economic forces strongly influence the development, choice, and use of technological solutions—personal values, consumer acceptance, patent laws, availability of venture capital, federal/state/provincial regulations, support and taxes, media attention, and competition. Technological knowledge has proprietary features (patent, copyright, legal consideration of intellectual properties) and may require secrecy, which is a personal or employee responsibility. Decisions to develop, produce, or halt production of an innovation involve consideration of: alternatives; risks, costs, benefits, material and human resource limitations; and environmental issues. Human inventiveness in technological design has brought new risks and negative impacts as well as improvements to people and other species.

Relationships among Science, Technology, Society, and Environment.

> Technological progress often sparks advances [in technology, science, or mathematics] and sometimes can even create a whole new field of study. … Conversely, technology borrows from and is influenced by many other areas. … Science, [mathematics,] and technology are like conjoined [triplets]. While they have separate identities, they must remain inextricably connected in order to [flourish]. (ITEA, 2007, p. 44)

These interactions involve knowledge transfers and applications within, between, and amongst technologies, science, and mathematics that occur when a new user applies an existing idea in a different function or to different context.

"Technology has been called 'the engine of history' for the way in which its use drives changes in society; it influences cultural patterns, political movements, local and global economies, and everyday life" (ITEA, 2007, p. 56). Technological innovations are influenced by societal priorities and innovations (such as dynamite, oil exploration, hydroelectric dams, military devices, satellites, electronic communications, etc.) and influence societal actions. Explosives and mechanized warfare have allowed governments to impose their priorities on other governments. These encounters have been somewhat romanticized and were able to continue reasonably unaffected by public opinion until rapid video telecommunications started delivering the results of such actions to the public's dinnertime news.

Technology–environment influences can be positive or negative, direct or indirect, and slow or rapid. These issues involve how humans can devise technologies to conserve water, soil, and energy through such techniques as informed selecting, reusing, reducing, and recycling. “The entire lifecycle of a product must be taken into account before the product is created, from the materials and processes used in its production to its eventual disposal” (ITEA, 2007, p. 65). Decisions regarding the design and implementation of technologies involve the weighing of trade-offs between predicted positive and negative effects on the environment. Transfer of a technology from one context to another can cause changes and can affect effectiveness, risk-benefit, and consequences of established innovations (e.g., driftnet fishing, fish farming, recreational vehicles, etc.).

Lack of consideration for the environment has led to the most pressing STSE issues. Developing technologies for different cultures to satisfy their individual and shared needs, wants, and values are critical; however, it is necessary to think globally and act locally. The NAE (2002) stated:

> From a philosophical point of view, democratic principles imply that decisions affecting many people or the entire society should be made with as much public involvement as possible. … Increased citizen participation would add legitimacy to decisions about technology and make it more likely that the public would accept those decisions. (p. 4)

The decision whether to develop a technology is influenced by societal opinions and demands in addition to corporate cultures (ITEA, 2007). Various factors (e.g., advertising, the strength of the economy, the goals of a company, and the latest fads) contribute to shaping the design or demand for various technologies. The easy and rapid flow of ideas associated with the digital age has allowed uncensored information that has changed and will continue to change local perspectives and generate demand for innovations.

CLOSING REMARKS

The SMT framework described in this chapter has the potential to illustrate how current reforms in science and mathematics could be revitalized by taking advantage of the powerful results in literacy and science education research and in disciplinary literacy generally. Furthermore, it could provide insights how technology, computer science, and engineering can be incorporated into the school curriculum. The current K–10 curriculum in most provinces and states is overcrowded and packed with excessive topics and courses. BC has tried to address this overcrowding by reducing the number of topics in K–7 to three in-depth units of study and to four units in Grades 8–10.

It appears as if there is no appetite to reduce existing subjects in the curriculum to make room for new subjects like technology, computer science, and engineering. This was the case with environmental education (EE) and science and technology (S&T 11) in the past. There has been some success with infusing EE into the K–10 social studies curriculum. The BC MoE has developed and provided several resources to promote environmental education in schools and support students under the Green Schools initiative (http://www.bced.gov.bc.ca/greenschools/). Environmental learning and experiences for sustainability course content, guides and curriculum maps for fundamental principles (complexity, aesthetics, responsibility and ethics) onto K–12 science, social studies, mathematics, language arts, and fine arts. The experience with S&T 11 has not been as positive. First, BC universities did not accept S&T 11 as a certified science course for postsecondary entry. Second, this excellent course was then assumed to be for nonacademic students; therefore, many of the interesting topics and STSE issues were not pursued with rigor.

It is unlikely that technology, computer science, and engineering will be accepted as new K–12 disciplines. Therefore, it appears that an infusion (embedding technology, computer science, and engineering standards in other disciplinary standards like science, mathematics, and social studies), mapping (identifying connections between the big ideas of technology, computer science, and engineering with important concepts in other disciplines standards like science, mathematics, and social studies), or repackaging parts of an existing course into interdisciplinary unit strategies will be the only possibilities to introduce technology, computer science, and engineering to students with some rigor.

The USA reports on engineering standards (NAE, 2010) and the draft science education standards (NRC, 2010) have highlighted the importance of science and technology. But both of these documents and the mathematics standards (NCTM, 2000) imply that technology and engineering standards should be integrated into science and mathematics and not to stand alone, as ITEA (2007) has suggested. Clearly, a first step for most countries would be to identify existing curricular resources that focus on engineering, technology, and computer science and are associated with standards. A second step would be to use the framework for scientific, mathematical, and technological literacies as a basic architecture to identify appropriate points for infusion and mapping commonalities. A number of such materials are available in some provinces, the United Kingdom, and the USA (see FOSS, STC, Insight, and TRAC series for self-contained modules on design, models, and other technology/engineering topics). Later in this book, the chapters on computer science applications and robotics (Carruthers et al., Chapter 6 this book; Francis Pelton & Pelton, Chapter 7 this book) will provide insights into Pacific CRYSTAL resources and projects.

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