The University of Victoria Pacific Centre for Scientific and Technological Literacy is one of five Centres for Research into Youth, Science Teaching and Learning (CRYSTAL) funded for 5 years (2005–2010) by the Natural Sciences and Engineering Research Council Canada (NSERC). Pacific CRYSTAL intended to promote scientific, mathematical, and technological literacy for responsible citizenship through research partnerships with university and educational communities. Pacific CRYSTAL’s functional structure consisted of 3 research and development nodes connected to a leadership and administrative node, which was charged with facilitating the activities of 39 projects and 42 principal investigators, partners, and research associates. Node 1, an incubation centre, involved extracurricular authentic science, mathematics, and technology experiences; Node 2, a classroom testing environment, field-tested instructional ideas and strategies to develop evidence-based practices; and Node 3, lighthouse schools, involved systemic change and leadership opportunities that adapted, demonstrated, and disseminated tested ideas, resources, and strategies to a much broader education community and attempted to influence public policy. This book provides descriptions of the target goals, research and development projects, and lessons learned.
Pacific CRYSTAL Centre for Science, Mathematics, and Technology Literacy: Lessons Learned
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I. OVERVIEW, COMMON THEMES, AND THEORETICAL FRAMEWORKS
1. PACIFIC CRYSTAL CENTRE FOR SCIENCE, MATHEMATICS, AND TECHNOLOGY LITERACY: LESSONS LEARNED

Overview

The Centres for Research in Youth, Science Teaching and Learning (CRYSTAL; Natural Sciences and Engineering Research Council of Canada [NSERC], 2009) were funded by NSERC as a 5-year pilot project (2005–2010) to foster science and mathematics education research and development (R&D). These five Canadian centres (see Notes) focused on science, mathematics, and technology (SMT), including engineering and computer science, in response to the widespread and growing recognition that the SMT literacies are vital skills in the 21st century economy. CRYSTAL has provided a forum for the many partners who share an interest in developing and enhancing the skills of and resources available to teachers, nongovernmental agencies, and public awareness educators and in enriching the SMT preparation of young Canadians. The CRYSTAL projects have attempted to:

– improve understanding of the skills and resources needed to enhance the quality of science, mathematics, and technology education (K–12), and

– improve understanding of the best ways to enrich the preparation of youth in these foundation subjects.

The five interuniversity and interdisciplinary centres are composed of one or more universities and colleges, faculties of education, science and engineering, local community partners, and nongovernmental agencies. Partners and agencies were recruited from user groups that focused on the public awareness of SMT, First Nations, informal learning environments, public and private schools, and ministries of education.

CONCEPTUAL FOCUS AND ORGANIZATION OF PACIFIC CRYSTAL

Pacific CRYSTAL consisted of a partnership of universities (University of Victoria, Simon Fraser University, and Vancouver Island University [formerly Malaspina University College]), faculties within the universities (Education, Science, and Engineering), British Columbia school districts on Vancouver Island and the Lower Mainland, First Nations (Saanich First Nations including Tsartlip and Tsawout), and nongovernmental agencies (Canadian Geological Foundation, Centre for Excellence in Teaching and Learning Science, Constructivist Education Resources Network,
EdGEO, Victoria Foundation, SeaChange, and WestWind SeaLabs). Pacific CRYSTAL examined ways to improve SMT teaching and learning in elementary, middle, and secondary schools by building on Canada’s successful foundation, as demonstrated by recent (2003, 2006, 2009) general mathematics and scientific literacy performances on the Programme of International Student Assessment (PISA; Organisation for Economic Co-operation and Development [OECD], n.d.). General SMT literacies are focused on citizenship and active participation in society. Improving SMT literacies among youth as a whole helps address access and equity issues and increases the supply of students qualified for and interested in science, mathematics, engineering, and technology programs at postsecondary levels, thereby addressing the higher-level elite literacies related to SMT careers and the needs of the provincial, national, and international economies.

Pacific CRYSTAL and its projects emphasized research inquiries that develop and evaluate knowledge about SMT literacies, underserved and underrepresented peoples, and science and technology fields including biology (ocean ecosystems, botany), environmental science, earth science (weather, climate, geologic history, plate tectonics, natural hazards, resources), chemistry (water quality, qualitative and quantitative analyses), computer science (problem solving, graph theory, foundation concepts, programming, robotics), and mathematics (data displays, probability, geometry) in Years 1–3 (2005–2008). Greater emphasis was placed on education, professional development, and leadership for teachers, wider implementation, dissemination and outreach activities to influence public policies, education and curricular decisions, classroom practices, and instructional resources in Years 4–5 (2008–2010). A no-cost extension request was approved to complete ongoing projects, finalize resources, disseminate outcomes, and influence policy makers (Year 6, 2010–2011). Over the duration of the project, the participants changed (~30%) as projects were completed and graduate students finished their research programs. As well, the focus of the Centre and projects morphed to meet changing emphases and interpretations of the CRYSTAL program and to reflect the Centre’s successes, progress, and opportunities.

Pacific CRYSTAL established a mission statement through a deliberative process involving faculty members, partners, and research associates as a centre to promote scientific, mathematical, and technological literacy for responsible citizenship through research partnerships with university and educational communities. A strategic Build–Expand–Lead plan was developed in which ideas, resources, and research inquiries would evolve from small-scale authentic learning opportunities viewed as extra-curricular and outside the prescribed curriculum and school program (Build), to controlled applications of evidence-based classroom practices and resources (Expand), and to scaled dissemination and implementation, leadership experiences, and policy actions (Lead). The emphasis changed from small-scale authentic opportunities in the early years to classroom-scale trials in the middle years and finally to systemic-scale implementation, leadership, and knowledge transfer efforts in the final years. The partners identified project foci and intentions within the mission statement and formed three functional nodes under a central leadership and administration node at the University of Victoria, which was guided by (a) an
International Advisory Board of scientists, community members, science educators, and cognitive scientists, (b) an Executive Committee of principal investigators from the University of Victoria and community partners, and (c) Co-directors (see Appendix for complete listing of these groups).

The functional organization involved a hub-and-spoke model for administrative purposes, with the central management node radiating out to the three R&D nodes. However, as the projects developed, much more integration and collaboration occurred among the researchers and participants in the separate nodes. A central, intermodal goal was to increase the leadership capacity for SMT education through production of highly qualified personnel (HQP) for schools, partner agencies, and universities. Therefore, wherever possible, internships, graduate fellowships, and research apprenticeships were utilized to provide authentic experiences in SMT areas. While only some projects are featured in the following chapters, a listing of HQP, graduate projects, theses and dissertations, articles, conference presentations, chapters, reports, and instructional products is provided in the book’s Appendix.

Node 1 (Build) involved developing authentic experiences designed to provide real SMT opportunities to students and then documentation and evaluation of what happened in these experiences to assess their effectiveness in improving SMT literacies, fostering interest in the disciplines, and establishing disciplinary identity. Innovative experiences and approaches to SMT literacy included self-exploration of identity, career awareness, attitudes toward the disciplines; internships in university science laboratories, community education groups, and traditional and western knowledge about nature; field-based ecology programs; intertidal systems and aquaria in classrooms; hands-on earth science field trips and activities; and problem-solving workshops with computer science concepts. These experiences, applications, and resources were informed by constructivist pedagogies and self-efficacy as well as inquiry, design, and problem-solving based learning in both formal and informal learning environments.

Node 2 (Expand) involved implementing classroom experiences that provide a variety of instructional approaches regarding thinking, language, mathematics, and engineering design with unique resources and information communication technologies (ICT) to enhance SMT literacies. Research conducted on these approaches focused on establishing interdisciplinary relationships amongst science, mathematics, and language arts; integrating instructional resources and strategies developed in Node 1 into classroom experiences; examining science literacy through reading, writing, and oral discourse; and developing weather units and online assessment tools. Projects included explicit literacy instruction in middle schools; community mapping in environmental studies, socioscientific issues, earth science activities and strategies in teacher education and professional development; and use of automated weather stations, a weather unit, and an inventory of weather concepts. Teachers collaborating with researchers benefited and contributed professionally through involvement in the research projects, professional development workshops associated with the projects, and individual graduate research projects integrated with the node’s objectives.

Node 3 (Lead) involved researchers seeking to engage and build partnerships with teachers and to better understand and support the teacher’s role in improving
students’ SMT literacies and instruction. This node focused on hierarchical linear modeling (HLM) analyses of the PISA datasets for science, mathematics, and reading literacies to better understand the relationships between student performance and student, home, and community characteristics; implementing change, establishing a foundation for educational policy involving SMT education, developing model programs, and producing a legacy of SMT advocates and lead teachers. This node emphasized leadership through professional development, cascading leadership in which participants assumed responsibility for professional development activities as projects evolved, demonstration or lighthouse schools, teacher workshops, teacher involvement, and programs for preservice teachers. Lighthouse schools investigated the development of excellence in classroom instruction with school-wide professional development, resulting in K–5 science units, a water quality exploration, and environmental literacy, awareness, and activities. Teacher education in earth science was fostered through a specialized laboratory section for pre-Education students in a first year Earth and Ocean Science course. Leadership and knowledge transfer (also termed knowledge mobilization and knowledge utilization) were central to all projects in this node.

INTEGRATIVE THEMES AND IDEAS

Early efforts were devoted to shaping the mission statement and strategic evolution plan and to ensuring shared understanding of the goals and working frameworks amongst a diverse group of scientists, educators, and partners. These efforts identified a set of interconnected themes and ideas that crossed and integrated many of the independent projects within Pacific CRYSTAL, for example, constructivist learning and teaching approaches, SMT literacies, learner resources, informal and formal environments, professionalism, teacher education, professional learning and leadership, evidence-based practices, knowledge transfer, and policy advocacy.

Constructivist Learning and Teaching Approaches

Education—a horizontal knowledge structure—has conflicting or alternative views of learning that coexist without the normal evolution, integration, or replacement of competing views found in the vertical knowledge structure in the sciences and mathematics (Lerman, 2010). This allows views of learning, curricula, instruction, and assessment practices based on outdated or questionable foundations to exist (United States National Research Council [NRC], 2000, 2007). Science education and mathematics education are no exceptions since some views of learning and instruction are based on behaviourism (drill and practice, objective test items), while others are based on cognitive development (developmental appropriate tasks, performance assessments), and still others are based on cognitive psychology (socio-cultural, sociocognitive perspectives, authentic assessments). Some of these views do not recognize the importance of learners’ prior knowledge (including misconceptions, informal experiences, metacognition, language, and intuition), and they stress rote content learning and emphasize learner deficits (NRC, 2005a, 2005b, 2007).
“Students often have limited opportunities to understand or make sense of topics because many curricula have emphasized memory rather than understanding” (NRC, 2000, pp. 8–9).

The diverse participants in Pacific CRYSTAL embraced constructivism and recognized that this view of learning includes a spectrum of views from information processing, interactive-constructivism, social constructivism, and radical constructivism (Henriques, 1997; Yore, 2003). Constructivist approaches consider learning as sense making; the nature of SMT; the constructive, persuasive, and communicative roles of language in doing and learning these disciplines; the importance of prior knowledge, values, and beliefs; cultural perspectives about these disciplines; intuitive reasoning, critical or creative thinking, reflection, and metacognition; and the utilization of these resources to construct understanding.

Most project leaders implicitly or explicitly endorsed centralist views of constructivism with a sociocognitive interpretation that considered sociocultural influences, group dynamics and negotiations, and individual reflection and sense making while emphasizing a balance of self-directed and teacher-guided approaches. Many of the pragmatic teaching approaches utilized some form of a modified learning cycle (SEEs [engage, explore, explain, elaborate, evaluate], EECA [engage, explore, consolidate, assess], or EDU [explore, discuss, understand]) and inquiry-oriented, problem-solving, and design-based approaches (teacher-structured, teacher-guided, open) involving hands-on experiences, multiple information sources, small-group negotiations, teacher-scaffolded discussions, and assessment for and of learning. These approaches assume that learners construct understanding based on their ontological assumptions, epistemological beliefs, prior knowledge, concurrent sensory experiences, available information sources, and interpersonal interactions within a sociocultural context. Teacher-directed instruction and modelling focused on requisite concepts or abilities are provided as just-in-time teaching on an as-needed basis, and the instruction considers the metacognitive awareness (declarative, procedural, and conditional knowledge) and executive control (planning, monitoring, regulating) necessary to facilitate students’ explorations and learning. Assessment for learning involved ongoing formative techniques that empowered learning and informed instruction, while assessment of learning involved summative techniques that provided cumulative information for evaluation and accountability purposes.

Science, Mathematics, and Technology Literacies

Participants were generally in agreement that science, mathematics, and technology are disciplines with unique but interconnected and related attributes. They were supportive of the idea that 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. Science is generally characterized as inquiry, mathematics as problem solving, and technology as design but all involve argumentation (AAAS, 1990; International Technology Education Association, 2007; United States National Academy of Engineering, 2010; United States National Council of Teachers of Mathematics, 2000; NRC, 1996, 2007).
Analyses of the USA reform documents in SMT indicated common goals, pedagogy and assessment focused on all students, disciplinary literacy, constructivist teaching approaches, and authentic assessments (Ford, Yore, & Anthony, 1997). However, even with international support of SMT literacies, there are no commonly shared definitions that provide a working framework and details. The lack of clear working frameworks for each of the SMT literacies, the central goal of the project, was identified as a requirement to improve Pacific CRYSTAL and to encourage integration across projects.

Collaboration among CRYSTAL Alberta, Pacific CRYSTAL, and the National Science Council of Taiwan resulted in mathematical and scientific literacy frameworks that provided fine structure to these literacies building on earlier analyses of the USA reform documents (Ford et al., 1997). The resulting frameworks for mathematics and scientific literacies and the development of a parallel framework for technological literacy are reported in Chapter 2 (Yore, this book). Special issues of the *International Journal of Science and Mathematics Education* (Anderson, Chiu, & Yore, 2010; Yore, Pimm, & Tuan, 2007) sought mathematics and science education research involving forms of these literacies. These IJSME special issues synthesized the current international and Canadian reforms to produce (a) parallel frameworks of mathematical and scientific literacy and (b) a secondary analyses of the 2000, 2003, and 2006 PISA results on literacies in reading, mathematics, and science. PISA, unlike other international assessments, used noncurricular definitions of these literacies, which morphed somewhat over the 2000–2006 period but retained focus on adult needs, real-world applications, and informational text (OECD, n.d.). The very high correlations (0.78–0.88) at student-level performances amongst reading, mathematics, and science literacies illustrate shared variances (61–77%) and potential associations amongst these literacies, which do not necessarily indicate causal relationships but are too large to ignore (Anderson et al., 2010). These results were used to support the interactive nature of fundamental literacy in a discipline and the derived understanding of that discipline found in the proposed frameworks.

Learner Resources: Prior Knowledge, Experiences, Beliefs, and Perceptions of Self

Learning theories and models prior to constructivism put much emphasis on learner qualities (IQ, logico-mathematical operations, socioeconomic background, etc.) as fixed traits unreceptive to change and growth. Therefore, many teaching approaches using these interpretations incorporated a *deficit model* in which instruction (e.g., learning assistance, special education, etc.) had to first address the deficit before the actual teaching and learning could occur. Applicants of constructivism incorporated the positive and negative lessons learned from these special approaches and re-engineered instruction to view all learner attributes as resources from and on which to facilitate learning. The basic principles are to ascertain what learners know and can do and then teach them accordingly (Ausubel, 1968) and to realize that teaching is in service of learning—without learning, teaching did not occur (Hand, 2007). Prior experiences and knowledge, including misconceptions, become springboards or foundations for further inquiries, designs, and problem solving.
Many students have misconceptions about the nature of SMT that influence learning (AAAS, 1993). Minority cultural beliefs and views of the SMT disciplines can be used to anchor instruction that respects sociocultural perspectives, enables honourable engagement, and guides the learning and teaching progressions.

Language is an important cognitive, persuasive, and communicative tool or technology in learning (NRC, 2000, 2007). It is documented that, like English language learners (ELL), most students in SMT courses face the 3-language problem involving transitions between home, school, and disciplinary languages (Yore & Treagust, 2006). Therefore, SMT students are science language learners (SLL), mathematics language learners (MLL), and technology language learners (TLL). The border crossings for some ELL, SLL, MLL, and TLL involve more than memorizing scientific, mathematical, and technological terminology; it involves being initiated into the culture, discourse, and metalanguage of these disciplines and into how language is used to construct, shape, justify, and report knowledge.

A major resource of interest for the underrepresented and underserved target populations of Pacific CRYSTAL were students’ identities in and with the SMT disciplines. The NRC (2007) stated, “Students’ motivation, their beliefs about science [and likely mathematics and technology], and their identities as learners affect their participation in the ... [SMT] classroom[s] and have consequences for the quality of their learning.” (p. 195). These identity attributes (i.e., cognitive—belief about self; emotional or affective—values, interest, motivation, and attitudes; and behavioural—persistence, effort, and attention) are captured under the general headings of “[s]elf-concept[, which] refers to global ideas about one’s identity and one’s role relations to others. ... [and s]elf-esteem[, which] refers to the value one places on himself or herself.” (Koballa & Glynn, 2007, p. 92). Both self-concept and self-esteem appear to be discipline- and context-specific where young people may have strong to weak interpretations of self in, for example, music, athletics, gangs, and academics.

The NRC (2007) suggested that students who have stronger beliefs and sense of competence in SMT tend to use deep learning strategies and exert more academic effort. Furthermore, there appear to be gender and cultural differences in these beliefs about role-stereotyped domains of SMT that may provide insights into the current and future participation, success, and career choices of underrepresented and underserved populations. The SMT cultures are “foreign to many students, both mainstream and nonmainstream, and the challenges of ... [SMT] learning may be greater for students whose cultural traditions are discontinuous with the way of knowing characteristic of [these disciplines and school programs in these disciplines]” (NRC, 2007, p. 201). de Abreu (2002) stated, that in mathematics education:

The need for a better account of the interplay between the cultural, social, and person systems is needed. ... There were issues related to the uniqueness of the individual and patterns of development in the reconstruction of the cultural tools at the person level and also issues related to the social valorization of knowledge, changes in social structures, and the person’s and the group’s sense of identity. (p. 341)

The NRC (2007) stated, “some students in a group may disidentify with a particular domain, like school or ... [SMT], due to widely held stereotypes about their lack of
ability in it. To protect their own sense of self, some students disidentify with the 
domain and stop trying to achieve in it.” (p. 197).

Self-efficacy is a more specific interpretation of self and identity involving “beliefs 
in one’s capabilities to organize and execute the courses of action required 
to produce given attainments” (Bandura, 1997, p. 3). Self-efficacy has two 
dimensions: beliefs about abilities and the expectation that these competencies can be 
successfully applied. Koballa and Glynn (2007) pointed out that self-efficacy within 
science and specific domains or topics were reasonable predictors of achievement 
and test performance; however, questionnaires that address specific areas may be 
more useful than those that address science generally. Such instruments have been 
developed for science and mathematics but not for technology (Enochs & Riggs, 
1990; Enochs, Smith, & Huinker, 2000).

Goal orientations, such as performance and mastery, provide insights into students’ 
intellectual resources and inform teaching. Performance orientation focuses on 
favourable evaluation while mastery orientation focuses on skill development, 
conceptual understanding, and learning. Performance orientation is well suited to test-
driven learning environments while mastery orientation is well suited to interactive-
constructivist learning environments where students and teachers collaborate to set 
the learning agenda.

Informal and Formal Environments

One goal of Pacific CRYSTAL was to use informal environments as an incubator 
for developing and evaluating authentic SMT learning activities that could then be 
implemented and disseminated to classroom and school environments and for 
the public awareness and engagement of SMT. (See comprehensive literature review 
provided a comprehensive overview and value-added insights of informal environ-
ments beyond classrooms and schools. The “narrow focus on traditional academic 
activities and learning outcomes is fundamentally at odds with the ways in which 
individuals learn across various social settings: … in potentially all the places they 
experience and pursuits they take on” (p. 27). The report recognizes life-long, life-
wide, and life-deep learning and the significant contribution that lived experiences 
make to formal learning within constructivist, people-centred, place-centred, and 
culture-centred learning. The “[s]tandardized, multiple-choice test, [which] has 
become monoculture species for demonstrating outcomes in the K–12 education 
system, is at odds with the types of activities, learning and reasons for participation 
that characterize informal experiences” (p. 56). Formal assessments of learning 
are antithetical to assessment for self-directed learning, and these techniques may 
threaten learners’ self-esteem and self-concept of the SMT activities. “In sum, 
although the nature and extent of … [SMT]-related learning may vary considerably 
from one life stage to another, most people develop relevant abilities and intuitive 
knowledge from the days immediately after birth and expand on these in later stages 
of their life.” (p. 99).
Informal environments include people-built designed settings, programs for various age groups, and media. Designed settings (including exhibits, demonstrations, and programs at institutions such as museums, science centres, aquaria, and environmental centres) are fluid spaces to be engaged with episodically and navigated freely, with limited or no directions, guidance, and facilitation by external scaffolding or staff to explore the target ideas emphasized by the design features. Programs—including after-school and out-of-school learning programs for children and youth, adult programs such as citizen science programs and teacher professional development programs, as well as programs for older adults—reflect societal changes in childcare, career changes, and leisure time. After-school, weekend, and summer programs (e.g., robotics contests, girls in science, and Science Venture) can cause tensions with in-school programs. However, Pacific CRYSTAL research and learning initiatives clearly supported the belief that “The potential of programs for ... [SMT] learning is great, given the broader population patterns” and require careful consideration, research, documentation, and evaluation (NRC, 2009, p. 199). Informal environments can address diversity, culture, and equity issues faced by underrepresented and underserved populations since many of these issues have their roots in other educational systems and lack of opportunities. “Environments should be developed in ways that expressly draw upon participants’ cultural practices, including everyday language, linguistic practices and common cultural experiences” (pp. 236–237). Mass and interactive media (e.g., print, education broadcast, popular entertainment, and other immersive media—IMAX, planetaria, laser-projection systems) have significant roles in the public awareness and engagement. “[SMT]-related media are likely to continue to play a major role in the ways that people learn about ... [SMT] informally. The public often cites broadcast, print and digital media as their major sources of scientific[, mathematical, and technological] information.” (p. 277).

**Professionalsm, Teacher Education, Professional Learning, and Leadership**

Professions—communities of practice regulated by defined associations, authorities, or judicial panels—control entrance, acceptable practices, ethical conduct, and discipline. Teaching professions are not as tightly controlled as the accounting, engineering, legal, medical, or other recognized professions. Colleges of teachers or provincial governments control licensure requirements for initial entry into teaching and teacher education programs directly or indirectly in Canada. Some school districts require or encourage continued professional learning or advanced degrees to maintain effectiveness and to progress to higher levels of salary structures. Universities, professional associations, and school districts can formally offer these experiences as credit or noncredit courses. There is reasonable evidence that high-quality professional development and high-quality instructional resources will change classroom practices, but there is very limited evidence that this triad leads to improved student achievement (Shymansky, Yore, Annetta, & Everett, 2008).

There is a growing realization that initial teacher education programs cannot provide the content (CK), pedagogical (PK), and pedagogical-content (PCK) knowledge for career-long, effective performance in rapidly changing classrooms and
curricular contexts. Many teachers desire personalized approaches that value self-directed or community-based professional learning to maintain or enhance effectiveness and to address the ever-changing curriculum and instructional demands. The US National Board for Professional Teaching Standards (NBPTS) certificate is one such post-entry program designed to improve high-quality professionalism, classroom practice, and school leadership (http://www.nbpts.org/). Central requirements of NBPTS certificates are evaluation, reflection, regulation, and justification of curricular, instructional, and assessment decisions about preparing for and establishing favourable contexts, and advancing and supporting student learning by professional teachers. This places prime importance on rational, evidence-based decisions about what to teach, how to teach, and what data justify learning and teaching effectiveness.

Many of the Pacific CRYSTAL projects focused on teacher enhancement, curriculum development, and instructional resources that attempted to utilize authentic learning activities and leadership opportunities from informal environments to develop leaders, evidence-based practices, and tested resources for classroom and school environments. Therefore, internships, professional development experiences, fellowships, and apprenticeships were utilized to provide authentic learning, teaching, research, and leadership experiences for the SMT education areas. These experiences used community-based designs to (a) identify needs and set agendas, (b) deliver professional learning experiences focused on CK, PK, and PCK, and (c) provide mentoring and peer tutoring between and amongst university, school, First Nations, and nongovernmental participants within the realities of SMT research, development, and teaching.

Evidence-based Practices

Millar and Osborne (2009) considered practices that might have sufficient evidential-basis and suggested that wait time (Rowe, 1974a, 1974b), formative assessment (Black & Wiliam, 1998a, 1998b), and cognitive acceleration (Adey & Shayer, 1990) had enough research support for such acceptance and teacher uptake. Interestingly, learning styles and inquiry teaching, although popular with teachers or widely promoted in education literature, do not appear to enjoy the same degree of evidence or actual teacher uptake. These and other instructional practices appear to be popularized by promotional efforts but not empirical research findings.

The evidence-based practice model requires that (a) practitioners (here, teachers of SMT literacy) read the research on curricular and instructional practices, (b) this research addresses teachers as the target audience and end users, and (c) professional codes and recommendations are based on quality research results in sufficient quantity and consistency to define best practices (Hayward & Phillips, 2009). The US Institute for Educational Sciences provided standards for quality of evidence considered to be strong, possible, or weak for specific instructional programs, resources, and practices based on research design, rigorous methods, valid and reliable measurements, comprehensive data sources, appropriate data analysis, and compelling arguments involving legitimate claims, strong theoretical backings, and sound warrants of the data as evidence for or against specific claims or counterclaims (Shelley, 2009).
Recent analyses of science teacher journal articles dealing with scientific literacy from Australia, the United Kingdom, and the United States revealed that most recommended literacy strategies and activities were poorly justified (Hand, Yore, Jagger, & Prain, 2010). A more in-depth analysis of the 1998–2009 National Science Teachers Association journals for elementary, middle, and secondary school teachers on the same topic revealed that 61% of the recommendations were based on no or weak evidence (Jagger & Yore, 2010). Several North American agencies provided synthesis of evidence and have identified best practices:

- Best Evidence Encyclopedia (http://www.bestevidence.org/)
- The Campbell Collaboration (http://www.campbellcollaboration.org/)
- Comprehensive School Reform Quality Center (http://www.csrq.org/)
- What Works Clearinghouse (http://ies.ed.gov/ncee/wwc/)

Pacific CRYSTAL has attempted to provide similar insights by means of its publications, presentations, and resources.

Knowledge Transfer and Policy Advocacy

A central concern of the CRYSTAL project was for wider dissemination of its R&D results and the influence of public policy. It is widely recognized that writing research reports for highly regarded, peer-reviewed academic journals and assuming that end users (i.e., teachers, administrators, parents, bureaucrats, elected politicians) will access and use these results has not worked; few education policies are influenced by SMT education research. Successful knowledge transfer and policy influence involves much more; specifically, considering the end users from the outset and understanding the political structures and policy process, end users’ preferred access and sources of information, and normative values of the political context. Reporting to these audiences as intended targets and speaking truth to powerful people is a complex, poorly understood, and time-consuming process. Shelley (2009) stated, “In highly abbreviated form, the essential point is how to reach across the gulf that is created by an unequal distribution of power (researchers having rather little and decision makers having very much more) to transmit understanding to those who are able to compel binding decisions.” (p. 444). Unfortunately, “[a]mong policy makers and many scholars, educational research has a reputation of being amateurish, unscientific, and generally beside the point” (Henig, 2008, p. 357).

Research results are not the prime influence on public policy since research evidence or findings are more often used to confirm or justify a position rather than to inform or change positions (Rees, 2008). The structure, information flow, and decision process of most political organizations involve the ultimate decision makers—politicians, high-ranking appointees, etc. (first community), academics (second community), and policy advisers, consultants, research officers, support staff, lobbyists, special interest groups, advocates (third community) in the policy system (Cohn, 2006). Academics infrequently have direct access to the first community but may have direct or indirect access to the third community. The actors in the third community use knowledge and information to produce useful position papers or briefs in the language of decision makers and then disseminate them to influence or advise decision makers.
Effective communication with and persuasion of these end users mean using appropriate sources, format, language, and style; stressing cooperation and collaboration rather than conflict; and recognizing possible claims, counterclaims, and rebuttals. Members of the K–12 education and policy communities are more likely to rely on ICT and generalist journals rather than high-level, peer-reviewed research journals (Henig, 2008). Knowledge mobilization and lobby efforts need to provide information that recognizes the central function (persuasion) and the window of opportunity. The Society for Research in Child Development (n.d.), for example, prepares 2-page, research-based briefs on social policy topics concerning children, families, and other issues in print and electronic form that are concise and informative.

Canada, unlike many nations, does not have a national ministry or office of education. Education is a provincial or territorial mandate that is vigorously guarded; therefore, provincial and territorial ministries of education are the focal point for any lobby actions and policy influence. However, there have been nonbinding cooperatives of governmental education agencies focused on policy, curricula, and assessments. The Council of Ministers of Education, Canada (CMEC) is one of the few national entities—it is a collective of the ministers of education from the provinces and territories that comprise the nation.

The Victoria Declaration was developed by the ministers of education in September 1993 and provided a directive to harmonize education by promoting curriculum compatibility and assessment. The first initiative related to the Declaration was the development of the School Achievement Indicators Program, which assessed reading, writing, mathematics, and science performance of 13- and 16-year-old students until it was replaced by the Pan-Canadian Assessment Program. The CMEC next adopted the Pan-Canadian Protocol for Collaboration on School Curriculum, which recognized provincial jurisdiction for education and that, by sharing human and financial resources, the quality and efficiency of education could be increased. The first curriculum effort led to the Common Framework of Science Learning Outcomes, K to 12 (CMEC, 1997), a nationally (albeit that Quebec did not officially participate) developed curriculum document that harmonized learning goals and science instruction in Canadian schools to provide the highest quality of education.

The Western and Northern Protocol for Canada (WNPC; http://www.wncp.ca/) is a regional interprovincial and interterritorial collaboration (composed of British Columbia, Alberta, Saskatchewan, Manitoba, the Yukon, Northwest Territories, and Nunavut) formed to develop coordinated perspectives on some common curricular areas. The WNCP Common Curriculum Framework for K–9 Mathematics (2006) is a guide with learning outcomes that reflects general trends in international mathematics education reforms. No similar national or regional effort has addressed K–12 computer science, engineering, environmental, and technology education.

Royal task forces and commissions are used to build consensus and lay the foundation for policies in Canada and other countries. The deliberative mechanisms appear to be democratic processes, but they are not without political difficulties. Membership in these groups may be based on expertise, representation, or other criteria but, once formed, they all involve negotiation, persuasion, controversy, and compromise. Participants involved in science and mathematics education deliberations
and reforms have attested to the internal and external struggles in producing a document based on diverse input and lengthy deliberations.

Three international reports have potential for influencing science literacy around the world and to illustrate potential pathways for mathematics and technology literacies (Fensham, 2008; Osborne & Dillon, 2008; Rocard et al., 2007). These ‘plain talk’ reports identify problems, provide recommendations, and supportive justification that could be used by policy and decision makers to craft policy briefs and procedures that would improve the articulation and coordination of science education goals, resources, and efforts regarding formal schooling and public awareness of science. They serve as reasonable models for what could be done for mathematics and technology education.

Knowledge transfer and policy influence require synthesis of qualitative and quantitative research using metasynthesis, meta-analysis, and systematic review techniques or secondary analysis of data sets and multiple results. The Pacific CRYSTAL HLM project that analyzed the PISA 2003 and 2006 results (Anderson et al., 2010; Milford, Anderson, & Luo, Chapter 11 this book) illustrates attempts to repackage international survey data into meaningful evidence for policy makers and decision makers. Milford, Jagger, Yore, and Anderson (2010) used document analyses and informant interviews to document the influence of the Pan-Canadian Science Framework (CMEC, 1997) on provincial and territorial K–12 science curricula. They found that the Framework was pervasive in both general directions and design elements and in the specific direct use of the document in curriculum development initiatives in the ministries of education throughout the nation. However, the influences of reform-oriented actions take significant time to influence educational policy and depend on curriculum development and implementation itself, which functions in a 7- to 12-year cycle.

Another issue identified was the need for specific operational definitions for implementing and evaluating the reform. For example, the centrality of scientific literacy is not matched by a specific definition of its meaning in terms of curriculum and instruction. Furthermore, given that the Pan-Canadian Science Framework is now in its second decade, there is a need for attention to currency and relevancy to science and science education. These findings also likely apply to mathematics and technology education reforms.

OVERVIEW OF BOOK, SECTIONS, AND CHAPTERS

This book addresses lessons learned during 5 years of R&D. These lessons provide insights for funding agencies regarding SMT literacies and instruction and into collaborative partnerships involving multiple agencies, scaling implementation from single teachers and classrooms to wider dissemination to schools and district-wide settings, building leadership capacity amongst SMT teachers, knowledge transfer, and influencing SMT educational policy and decisions.

Section 1 provides readers insights into CRYSTAL and especially Pacific CRYSTAL. Chapter 1 provides an overview of the contextual and organizational goals, conceptual foundations, theoretical constructs, and integrative themes across
the projects as they evolved from concept to testing and dissemination. The integrative themes of many of the projects are constructivist learning, SMT literacies, community-based R&D models, partnerships, learner attributes, informal environments, professional learning or development, teacher education, leadership capacity, systemic change, evidence-based practices, knowledge transfer or mobilization, and policy advocacy. Chapter 2, Foundations of Scientific, Mathematical, and Technological Literacies—Common Themes and Theoretical Frameworks, provides the working definitions and theoretical backings and research support for the central focus of Pacific CRYSTAL. These discipline-specific literacies have been discussed for many years and serve as the focus of international education reforms, but they lack well-accepted definitions that incorporate conceptual understanding, literacy, and contextual applications.

Section II, Authentic Learning—Informal Environments and Extracurricular Science, Mathematics, and Technology Opportunities: Anchoring and Bridging Real-world, Cultural, and School Experiences, describes projects from Node 1 that focused on building conceptual ideas and transforming them into instructional practices. Chapter 3, Adolescents’ Science Career Aspirations Explored through Identity and Possible Selves, addresses making career decisions in secondary school—a challenging and often stressful experience for adolescents involving self-concept related to identity and self-efficacy. The Possible Selves Mapping Process is an experiential activity that is future-oriented and a personalized form of self-concept; it has direct relevance to how students’ views of themselves guide their work and educational behaviours. Chapter 4, Giving Voice to Science from Two Perspectives: A Case Study, reports on an ethnobotanical program involving six First Nations members over 6 years in which opportunities to explore traditional and western knowledge about nature and naturally occurring events were made available at the University of Victoria and SNIĆTEL (pronounced sneakwith, SENĆOTEN language for The Place of the Blue Grouse)—part of traditional territory utilized for hunting, fishing, shellfish gathering, and sacred ceremonies. Chapter 5, Seaquaria in Schools: Participatory Approaches in the Evaluation of an Exemplary Environmental Education Program, reports on the successful partnerships amongst nongovernmental agencies, schools, universities, and their communities that helped enliven a community of practice for public school educators in which all partners actively participated in setting agendas and developing programs. The successes and challenges provide insights into how to achieve long-term sustainability through active community partnerships and how this approach can be applied elsewhere. Chapter 6, Teaching Problem Solving and Computer Science in the Schools: Concepts and Assessment, explores expanding the age range of students exposed to computer science and computer science concepts (i.e., recursion, concurrency, graph theory) through the development and deployment of interesting and engaging hands-on computer science activities. It discusses encouraging findings from three studies as well as the strengths and weaknesses of assessment techniques in various classroom settings. Chapter 7, Outreach Workshops, Applications, and Resources: Helping Teachers to Climb over the Science, Mathematics, and Technology Threshold by Engaging Their Classes, illustrates how elementary and middle school teachers who lacked confidence and
competence to teach SMT topics effectively adopted constructivist approaches. The outreach workshops made SMT topics more accessible to teachers by modelling the successful use of effective pedagogies, appropriate technologies, and authentic learning activities.

Section III, Moving Tested ideas into Classrooms, illustrates how conceptual ideas and practices were expanded and moved into larger settings. Chapter 8, Explicit Literacy Instruction Embedded in Middle School Science Classrooms: A Community-based Professional Development Project to Enhance Scientific Literacy, reports on the community-based project that identified, developed, and embedded explicit literacy instruction in science programs to achieve fundamental literacy in science and science understanding. Chapter 9, Enhancing Science Education through an Online Repository of Controversial, Socioscientific News Stories, reports an interactive teaching technique that employed controversial, socioscientific news stories as a means of developing scientific literacy and follows the development of the Science Times resource, its effectiveness and potential uses in similar learning opportunities and the larger learning community via Internet delivery. Chapter 10, Promoting Earth Science Teaching and Learning: Inquiry-based Activities and Resources Anchoring Teacher Professional Development and Education, focuses on developing teachers’ interest in and positive attitudes toward Earth Science and to increase PCK and experience with scientific reasoning and practice. A series of inquiry-based activities and accompanying resources were developed for teacher professional development workshops, an Education Laboratory in a first year Earth and Ocean Sciences course that demonstrates relevance, constructivist approach, curriculum linkages, opportunities for interdisciplinary associations (including language arts, mathematics, and other sciences) and accompanying resources are key attributes of these successful activities, which are classroom tested and informed by teacher feedback.

Section IV, Knowledge Transfer, Systemic Implementation, and Building Leadership Capacity, addresses the lead phase of the evolutionary strategy. Chapter 11, Modelling of Large-scale PISA Assessment Data: Science and Mathematics Literacy, investigates relationships and patterns associated with student performance in the literacies of mathematics, science, and reading and student, school, home, and community characteristics. The PISA data sets were the central foci of the investigations using HLM. The findings reported go well beyond simple ranking of participating nations in terms of average performance scores. Chapter 12, Time and Teacher Control in Curriculum Adoption: Lessons from the Lighthouse Schools Project, reports on case studies involving an elementary and a middle school where teachers were provided with funding that enabled them to have the time to implement a new science education curriculum and total control over the change process. Initially conceived as a lighthouse project of peer interschool development, the teachers involved reconceptualized the lighthouse to serve their particular, local interests. Teacher control translated into unit planning and changes in the direction of funding support toward the middle school receiving students from the elementary school. While teachers were enthusiastic about this change in process and the availability of time to plan, analysis of the science education units developed at
both schools revealed that curriculum change is complex and difficult, not easily addressed by providing time for planning, or by locating teachers as the sole agents of the change process. Chapter 13, The Development of a Place-based Learning Environment at the Bowen Island Community School, describes and documents one elementary lighthouse school’s experiences in achieving its environmental literacy goals through the development of a place-based learning environment. The Ecological Education Project studied the complex ecology of the intersection between scientific knowledge, pedagogy, student learning, and curriculum. They identified and developed innovative approaches for the teaching of scientific and interdisciplinary topics around environmental education framed within the context of ecoliteracy.

Section V: Closing Remarks and Implications for the Future, provides a post hoc perspective to highlight themes that evolved from individual projects. Chapter 14, Epilogue of Pacific CRYSTAL—Lessons Learned about Science, Mathematics, and Technology Literacy, Teaching and Learning, provides a cross-case analysis and discussion of the themes emerging from the studies reported in this book. The common themes across these studies were community commitment and action planning, disciplinary literacy (science, mathematics, technology), evidence-based resources and practices, professional learning (teacher education and professional development), student performance (conceptual understanding, fundamental literacy, self-efficacy, identity), and educational leadership and advocacy.

The Appendix offers a listing of highly qualified personnel—postdoctoral and graduate students, undergraduate research assistants, and community interns—involved with Pacific CRYSTAL. It summarizes their contributions, including theses and dissertations, articles, conference presentations, and instructional resources. This Appendix documents the legacy of the Pacific CRYSTAL Project more so than any other document.

CLOSING REMARKS

Pacific CRYSTAL suggested a number of independent R&D projects in the original proposal to address the changed research and policy expectations of NSERC. As the project unfolded, both NSERC and the principal investigators in Pacific CRYSTAL became more realistic about the complexity of the central problems and the project design. Early R&D efforts involved a loose collection of diverse projects without the internal glue of a shared mission statement and strategic plan. Experiences during Year 1 led to national and project-wide deliberations and considerations of the central goals, organizational structure, operational procedures, and outcomes by the NSERC staff, project directors from the five CRYSTAL projects, and the Pacific CRYSTAL International Advisory Board, Executive Committee, and all participants. The traditional definitions of educational research (i.e., publication of peer-reviewed articles and presentation at international conferences) was revised to focus on teachers, policy makers, instructional resources, and a variety of local, provincial, and national professional conferences. The insights into processes and procedures are equally and likely more important than the number of peer-reviewed research articles, books, and chapters that flow from Pacific CRYSTAL. The following chapters
provide theoretical, empirical, and practical documentation for several claims about SMT literacy and programs that promote fuller engagement of SMT learning and problems.

NOTES

CRYSTAL Alberta at the University of Alberta, Edmonton, AB, provided national coordination for all Centres (http://www.edpolicystudies.ualberta.ca/en/CentresInstitutesAndNetworks/CRYSTALAlberta.aspx): CRYSTAL Atlantique at the University of New Brunswick, St. John, NB (http://www.crystalatlantique.ca/); Centre de Recherché sur l’Enseignement et l’Apprentissage des Sciences at the University of Sherbrooke, Quebec (http://creas.educ.usherbrooke.ca/); CRYSTAL Manitoba at the University of Manitoba, Winnipeg, MB (http://umanitoba.ca/outreach/crystal/); and Pacific CRYSTAL at the University of Victoria, BC (http://www.educ.uvic.ca/pacificcrystal/main.html).

REFERENCES


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APPENDIX

Pacific CRYSTAL Advisory Board and Executive Committee Members, Co-directors as on June 30, 2010

Advisory Board

Dr. Chris Barnes, Director, Neptune Project, University of Victoria
Dr. Phillip Bell, Co-director, LASER Project, University of Washington, Seattle, WA
Dr. Jacques De’sautels, Laval University, Montreal, PQ
Dr. Reg Mitchell, Department of Chemistry, University of Victoria
Dr. Stephen Norris, National Coordinator, CRYSTAL, University of Alberta, Edmonton, AB
Mr. Lionel Sander, President, Edvantage Press, Victoria, BC
Dr. Rachel Scarth, Director of Research Services, University of Victoria

Executive Committee

Dr. David W. Blades, Department of Curriculum and Instruction, University of Victoria
Ms. Cathy Carolsfeld, WestWind SeaLab Supplies, Victoria, BC
Dr. Yvonne Coady, Department of Computer Science, University of Victoria
Mr. Calvin Parsons, Strawberry Vale Elementary School, Victoria, BC
Dr. Leslee Francis Pelton, Department of Curriculum and Instruction, University of Victoria
Dr. Ulrike Stege, Department of Computer Science, University of Victoria
Ms. Nikki Wright, SeaChange Marine Conservation Society, Brentwood Bay, BC

Co-directors

Dr. Larry D. Yore, Department of Curriculum and Instruction, University of Victoria
Dr. Eileen Van der Flier-Keller, School of Earth and Ocean Sciences, University of Victoria
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,
YORE

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
genagement 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, reparable
ability 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 engineer-
ning 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 mathe-
matics 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; mathe-
matical literacy—patterns and relationships of quantity, order, and shape; techno-
logical 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 [techno-
scientific] 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>
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<th>Year</th>
<th>Mathematics</th>
<th>Science</th>
<th>Reading</th>
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<td>2000</td>
<td>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.</td>
<td>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.</td>
<td>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.</td>
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<td>2003</td>
<td>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.</td>
<td>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.</td>
<td>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.</td>
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<tr>
<td>2006</td>
<td>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.</td>
<td>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.</td>
<td>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.</td>
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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)

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

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)

<table>
<thead>
<tr>
<th>Fundamental sense</th>
<th>Derived sense</th>
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<tr>
<td>Cognitive and Metacognitive Abilities</td>
<td>Understanding the Big Ideas, Strands, and Substrands of Mathematics</td>
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<tr>
<td>Mathematical Thinking and Quantitative Reasoning</td>
<td>Nature of Mathematics</td>
</tr>
<tr>
<td>Habits of Mind</td>
<td>Knowledge about Problem Solving</td>
</tr>
<tr>
<td>Language of Mathematics (including proofs as arguments)</td>
<td>Real-world Problems</td>
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<tr>
<td>Information Communication Technologies (ICT)</td>
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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 skillful 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, 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, collaborate, etc.), communications (concept sketches and final drawings, 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)

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<td>Habits of Mind</td>
<td>Technological Design</td>
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<tr>
<td>Technological Language (including Mathematics)</td>
<td>Designed World</td>
</tr>
<tr>
<td>Information Communication</td>
<td>Relationships among Science, Technology, Society and Environment (STSE)</td>
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<td>Technologies (ICT)</td>
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...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
Foundations of SMT Literacies

- 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, ongoing 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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