International Journal of Environmental & Science Education
Vol. 4, No. 3, July 2009, 301-311

SPECIAL ISSUE ON SCIENTIFIC LITERACY
Editors: Richard K. Coll & Neil Taylor

Beyond Science Literacy: Science and the Public

Xiufeng Liu

State University of New York at Buffalo, USA

Received 15 December 2008; Accepted 03 February 2009

The late 20th century and beginning of 21st century have witnessed unprecedented rapid economic development due to advances in technology and globalization. In response to this development, a renewed call for science literacy has become louder in the USA and many other countries. Common to all science education reforms around the world is emphasis on achieving science literacy by all children before high school graduation. This paper first reviews definitions of science literacy in the literature; it then examines the status of science literacy in the USA and other countries. Following the above, this paper then presents a new notion of science literacy as life-long participation in science – science and the public. This new notion expands science literacy to recognize it as both extrinsic and intrinsic, and as a state and a life-long process, which expands science literacy from school science to ongoing participation in science activities in society by citizens of all ages. This paper finally discusses two necessary approaches to achieving the expanded science literacy that include bridging formal and informal science education, and training science and the public educators through graduate programs on science and the public.

Key Words: science literacy, science and the public, informal science education, life-long learning, public engagement in science

Introduction

The late 20th century and beginning of 21st century have witnessed unprecedented rapid economic development due to advances in technology and globalization. The world has become 'flat' by such changing forces as work-flow software, out-sourcing, off-shoring, and informing (Friedman, 2006). Never before has a nation's economic development become so dependent on advances in science and technology creating demand for technical workers and a scientifically literate populace.

As the result, a renewed call to reform science education has become louder in the US and in many other countries. Examples of such calls for science education reforms include the US *National Science Education Standards* (National Research Council, 1996), the Canadian *Common framework of science learning outcomes* (Council of Ministers of Education, 1997), and the *National Curriculum for England* (Department of Education and Employment, 1999). Common to all science education reforms around the world, is the expectation for achieving science literacy by all children before high school graduation. In this paper, I will first review

ISSN 1306-3065

http://www.ijese.com/

definitions of science literacy in the literature and the status of science literacy in the US and other countries; I will then argue for a new conception of science literacy that is based on life-long participation in science. Finally, I will discuss two necessary approaches to achieving the new science literacy that include bridging formal and informal science education, and training science and the public educators through graduate programs in science and the public.

Definitions of Science Literacy

First of all, let us clarify the terms of science literacy and scientific literacy. Often reform documents use both without distinction. For example, *Science for All Americans* (American Association for the Advancement of Science [AAAS], 1989) uses the term science literacy, while the *National Science Education Standards* (National Research Council [NRC], 1996) uses the term scientific literacy. I agree with James Rutherford, director of Project 2061 at AAAS, that science literacy should refer to *literacy with regard to science*, while scientific literacy refers to *scientific nature of literacy* in all forms such as science, English language, technology, and so on (Roberts, 2007). In this paper, science literacy is related to goals of science education, and scientific literacy is related to approaches to achieving science literacy. The first part of this paper deals with science literacy, and the latter part of the paper deals with how to achieve science literacy – scientific literacy.

There is no universally accepted definition of science literacy (Roberts, 2007). In the 1960s, science literacy was perceived to be desirable for those who would not go to higher education; thus science literacy was less demanding than ‘science’ (Hurd, 1958). From the 1970s, science literacy has been perceived as desirable for *all* students, no matter what background, ability, and interest (DeBoer, 1991). Shen (1975) identified six elements of science literacy to be: (a) understanding basic science concepts, (b) understanding nature of science, (c) understanding ethics guiding scientists’ work, (d) understanding interrelationships between science and society, (e) understanding interrelationship between science and humanities, and (f) understanding the relationships and differences between science and technology. Based on the six elements, Shen (1975) further proposed three types of science literacy that includes (a) practical: possession of the kind of scientific knowledge that can be used to help solve practical problems, (b) civic: to enable the citizen to become more aware of science and science-related issues in order to participate in the democratic processes, and (c) cultural: knowledge and appreciation of science as a major human achievement and cultural heritage. The above three types of science literacy suggest that different types of science literacy may be appropriate for different people.

The differentiated notion of science literacy is also expressed by others. For example, Gabel (1976) conceptualizes science literacy as a two-dimensional matrix, with one dimension dealing with types of contents such as concepts, nature of science, relationships between science and technology, and so on, and another dimension dealing with types of reasoning and affective actions such as Bloom’s taxonomy of cognitive levels (knowing, understanding, applying, analyzing, synthesizing, and evaluating), and affective levels (receiving, responding, valuing, organizing, characterizing). Thus, according to Gabel (1976), science literacy may exist in different forms and degrees. Similarly, Shamos (1995) identifies three levels of science literacy: (a) cultural science literacy: a grasp of certain background information underlying basic communication, (b) functional science literacy: not only know the science terms, but also be able to converse, read, and write coherently using these terms in non-technical contexts, and (c) true science literacy: understand the overall scientific enterprise and the major conceptual schemes of science, in addition to specific elements of scientific investigation.

Recognizing the difficulty of achieving a true science literacy, Bybee (1997) conceptualizes science literacy as a continuum from nominal literacy to functional literacy to conceptual and procedural literacy and finally to multi-dimensional literacy. Nominal literacy refers to associating names with general areas of science and technology without accurate understanding (i.e., misconceptions). Functional literacy refers to reading and writing passages with simple scientific vocabulary. Conceptual and procedural literacy refers to understanding the structure of a science discipline and procedures for developing new knowledge. And multi-dimensional literacy refers to understanding not only the structure of science and technology, both also the nature of science and technology and their relationships with society.

The broadest notion of science literacy has been given by the American Association for Advancement of Science (AAAS). It defines science literacy as encompassing mathematics and technology as well as the natural and social sciences (AAAS, 1989). According to AAAS, a scientifically literate person is one who is aware that science, mathematics, and technology are interdependent human enterprises with strengths and limitations, who understands key concepts and principles of science, who is familiar with the natural world and recognizes both its diversity and unity, and who uses scientific knowledge and scientific ways of thinking for individual and social purposes. A more recent and less ambitious notion of science literacy is given by the National Research Council (1996) in which science literacy is considered to include understanding of unifying science concepts and processes, science as inquiry, physical science, life science, earth and space sciences, science and technology, science in personal and social perspectives, and history and nature of science.

The most recent attempt to define science literacy was undertaken by another National Research Council committee on science learning, kindergarten through eighth grade (NRC, 2007). Although the committee used a different term, that is, scientific proficiency, its intention for scientific proficiency to become the goal for school science education is the same as that of science literacy used in literature. According to the committee, scientific proficiency consists of four strands: (a) knowing, using and interpreting scientific explanations of the nature world; (b) generating and evaluating scientific evidence and explanations; (c) understanding the nature and development of scientific knowledge; and (d) participate productively in scientific practices and discourse. The above four strands share many commonalities with science literacy elaborated in the National Science Education Standards (NRC, 1996). One noticeable difference may be in the last strand in which more emphasis is placed on practicing scientific practices and discourse in a mini-society – the classroom.

Regardless of one's definition, arguments for science literacy are diverse and can be categorized as the following (Laetsch, 1987): (a) science literacy enables better political decisions, (b) science literacy enables better economic returns, (c) science literacy helps reduce superstition, (d) science literacy enables improved individual behaviors, and (e) science literacy helps to create a more ethical world. Similarly, the most recent National Research Council committee emphasizes that science should be nonnegotiable a part of basic education, because some knowledge of science is essential for everyone (NRC, 2007). Specifically, school science education should promote scientific proficiency because:

1. Science is a significant part of human culture and represents one of the pinnacles of human thinking capacity;
2. It provides a laboratory of common experience for development of language, logic, and problem-solving skills in the classroom;
3. A democracy demands that its citizens make personal and community decisions about issues in which scientific information plays a fundamental role, and they hence need a knowledge of science as well as an understanding of scientific methodology;

4. For some students, it will become a lifelong vocation or avocation; and
5. The nation is dependent on the technical and scientific abilities of its citizens for its economic competitiveness and national needs. (NRC, 2007, p. 34)

No doubt, science literacy is regarded as a noble goal; achieving it is highly desirable. Further, common to science content standards in all countries (e.g., AAAS, 1993; NRC, 1996, 2007) is the assumption that, by the end of high school, that is, grade 12, students should, and can, achieve science literacy.

Status of Science Literacy

Achieving science literacy has proven to be no easy task. Research in the past four decades has documented wide-spread misconceptions of basic scientific concepts among K-16 students (Baker, 2004; Wandersee, Mintzes & Novak, 1994). The US National Assessment of Educational Progress (NAEP), the nation's report card, indicates that only 18% of grade 12 students achieved the proficiency level – a level considered to be minimally scientifically literate (National Center for Educational Statistics, 2006). If students graduating from the US high schools have not achieved the level of expected science literacy, how can we expect the general public to achieve it? Statistics show that the picture is quite pessimistic in the USA and in other countries around the world. According to the 2008 Science and Engineering Indicators (National Science Board, 2008), the percentage of adults in selected countries answering correctly questions related to basic science concepts and principles, such as laser and genetic heredity, is quite low (<40% for most questions). Although percentages of adults understanding fundamental science concepts and principles vary greatly from country to country and from topic to topic, no consistent evidence suggests that there is a high level of science literacy among adults. Longitudinal assessment of science literacy in the US general population indicates that the level of science literacy has not changed for the past few decades, remaining at between 5-10% (Miller, 1987). It is doubtful that the rate of science literacy among adults has changed much since 1987. Keep in mind that, science literacy among adults assessed in the above mentioned studies on public understanding of science is only based on simple facts; it does not come close to the science literacy in any functional, civic, practical, cultural, or true sense reviewed earlier. An assessment of science literacy in a more comprehensive sense as defined earlier in this paper would no doubt produce an even more depressing picture on status of adult science literacy in the US and likely in other countries as well.

On the other hand, percentages of the general public believing in pseudoscience remain relatively high. Figure 1 presents the trend. The literature cited above on the status of science literacy by school students and adults suggest that science literacy remains a distant goal for students and adults in both the US and other countries. Is science literacy a too high goal to achieve? Indeed, Shamos has claimed that science literacy is a myth (Shamos, 1995). He argues that a meaningful science literacy, that is, the true science literacy, cannot be achieved in the first place, and the attempt is a misuse of human resources on a grand scale. Therefore, he suggests that science education should emphasize developing an appreciation of science as an ongoing cultural enterprise; an awareness of technology's impact on one's personal health, safety, and surroundings; and the need to use expertise wisely in resolving science/society issues, which is called new science literacy (Shamos, 1995). Miller suggests that efforts for science literacy may have to be scaled down to target just a few population strata, that is, decision makers, policy leaders, and the attentive public, while leaving a large percentage of non-attentive public out of science literacy (Miller, 1987).

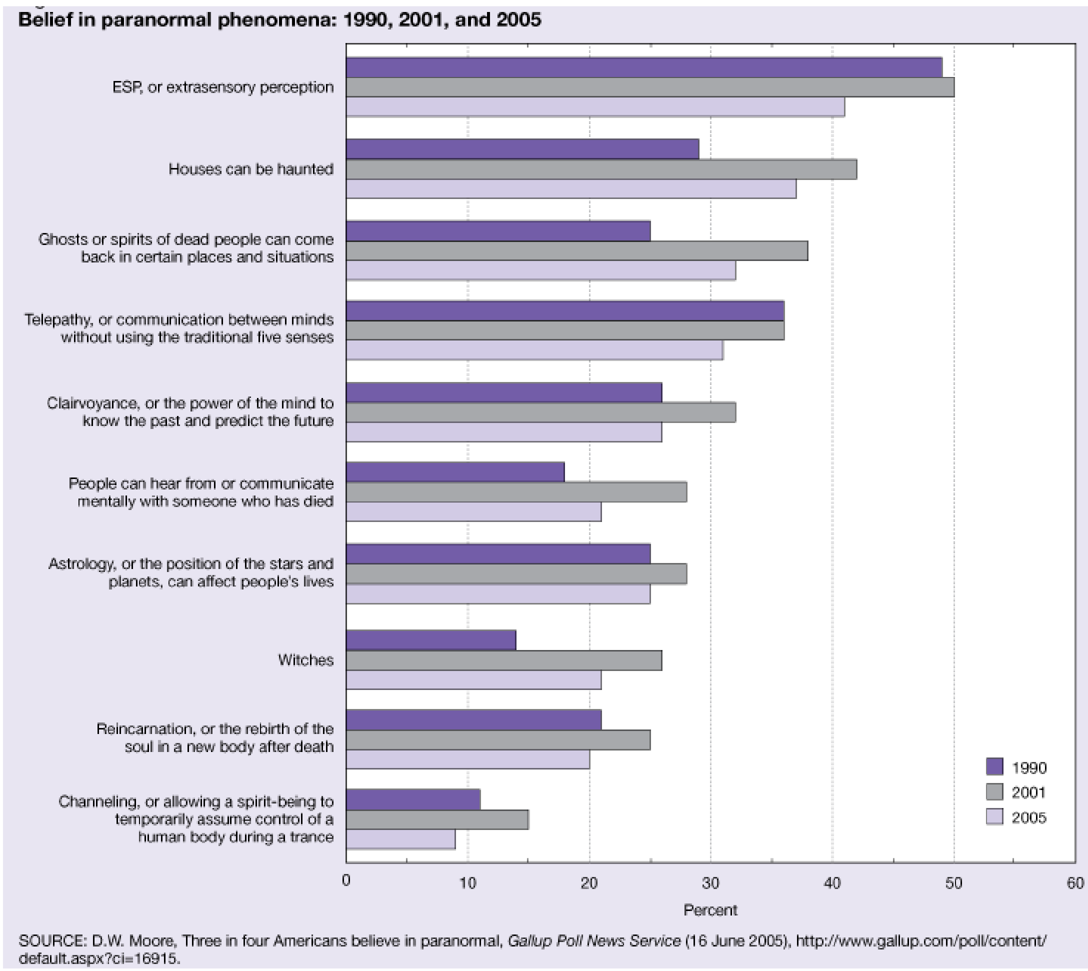

Figure 1. Beliefs in paranormal among Americans (National Science Board, 2008)

Reconceptualizing Science Literacy

Instead of retreating from a general campaign for science literacy, we may want to re-evaluate our notion of what it means by science literacy, and decide new strategies accordingly. The current notions of science literacy suffer from at least three flaws: (a) they are based on a 'deficit model', (b) they are based on a 'commodity model', and (c) they are based on a 'static model'. In terms of the first flaw, all current notions of science literacy assume that students and the general public lack of science literacy, thus they need to correct this deficiency. This deficit model ignores the fact that students and the general public do have a wide variety of informal knowledge and experiences about natural and life phenomena. Although their informal knowledge and experiences may not be totally compatible with the commonly accepted scientific views, they are 'functional' in everyday contexts because they seem to explain various phenomena to their own satisfaction. Research has shown that changing conceptions from everyday knowledge to scientific conceptions is not an easy task, because students and the general public may not easily appreciate that their conceptions are unsatisfactory, and that the scientific conceptions are intelligible, plausible, and fruitful (Posner, Hewson & Gertzog, 1982). Pintrich, Marx and Boyle (1993), adopting a social and affective perspective, argue that conceptual change should not just refer to changes in "cold and isolated cognition" (p. 167), it should also recognize the important moderating roles of motivational beliefs and contexts. The deficit model of science literacy ignores the active role of learners play in science literacy. It considers science literacy as being extrinsic to individuals, that is, tools for economic development and national security. Laetsch (1987) claims that previous and current notions of science literacy overlook the intrinsic nature of science literacy – the internal desires of individuals. Garrison and Lawwill (1992) question the morality of imposing a science literacy on students in terms of economic competitiveness by stating that "chaining science and science education to the goal of maximizing the economic production function … is immoral ... because it treats students as means to the pecuniary ends of others" (p. 343). Indeed, curriculum standard documents such as the National Science Education Standards have been called political documents (Collins, 1998). Critics have claimed that these notions of science literacy serve to maintain the dominance of special interest groups such as the elites or technocrats – those with political and economic power, while excluding others – particularly minorities (Aikenhead, 2006; Apple, 1992; Osborne & Calabrese-Barton, 2000).

The second flaw treats science literacy as a state to achieve or commodity to acquire, while ignoring science literacy also as a life-long process with practical, useful consequences to both individuals and societies. For example, the Benchmarks for Science Literacy (AAAS, 1993), and the National Science Education Standards (NRC, 1996) all specify what science literacy is in terms of learning outcomes to achieve. It assumes that if a person has achieved these outcomes, then the person has obtained science literacy. This notion of science literacy simply ignores the fact that science is constantly evolving, and that even an expert in one field of science may be ignorant in other science fields thus in need of knowing more. UNESCO defines that literacy involves a continuum of learning to enable an individual to achieve his or her goals, to develop his or her knowledge and potential, and to participate fully in the wider society. Science literacy should be an evolving state instead of a status to acquire. People constantly learn science in and outside school, within and outside work, and both formally and informally. Learning science is indeed a life-long process, rather than the goal to achieve once for all.

The third flaw deals with science literacy as a one-way flow of information from the knowledgeable to the less knowledgeable. Especially, the science information is considered unproblematic, universal, and value free. Roberts (2007) calls this context-free notion of science literacy Vision I as compared to situated science literacy of Vision II. Vision I science literacy ignores the necessity of science literacy as participation in science activities in society by citizens of all ages. This participatory notion of science literacy has been called community and citizenship-based science literacy (Roth, 2002; Roth & Calabrese, 2004; Roth & Lee, 2004). Science literacy is never context free; it is meaningful only when it relates to specific people, addresses specific issues, and aims at specific purposes (Jenkins, 1997).

There has also been other criticism about current notions of science literacy in the literature. For example, Hand et al. (2003) state that the current notions of science literacy neglect the important role of language uses in science. A science literacy with a consideration of language values both formal literacy learned in school and informal literacy practiced outside school. It also values a variety of ways of communications in science, particularly in reading, writing and speaking in science. In this sense, science literacy is a public good; it is the civic duty for all citizens. Similarly, Norris and Phillips (2003) distinguished two emphases of science literacy – the fundamental sense in terms of reading and writing in science, and the derived sense in terms of knowledgeable and competence in science. They further claim that current notions of science literacy often focus on derived sense while ignoring the fundamental sense.

Given the above, the unsatisfactory state of science literacy by school children and adults may be due to our outdated notion of science literacy. Broadening the notion of science literacy by including both extrinsic and intrinsic aspects and considering science literacy as a life-long process is necessary and consistent with current views of how people learn. Current learning theories recognize the importance of both formal and informal education, and effective learning takes place in both formal and informal settings. This view of learning reflects the fact that school children spend far more time outside schools than inside schools. According to an estimate (Bransford, Brown & Cocking, 2000), an individual spends only 18% of his or her life in schools, 5% before kindergarten, and 77% out of school years. During a typical school year, assuming 180 school days a year, 6.5 hours per school day, a typical American child spends 53% of time in home and community, 33% sleeping, and only 14% in schools. It seems clear that we have expected too much of children to achieve science literacy in school by the time they graduate from high school; we have overlooked much larger learning resources and potentials outside schools and beyond high school. Re-conceptualizing science literacy as both a state and life long process, as both a personal choice and an economic necessity, and as both a personal enhancement and civic participation expands science education from being merely school-based to all activities taking place both inside and outside schools, which creates a much greater potential for achieving science literacy by all citizens. This expanded notion of science literacy may be called science and the public.

Toward Realizing Science and the Public

If we accept the notion of science literacy as science and the public, two approaches are necessary for realizing it: bridging formal and informal science education, and training science and the public educators through graduate programs.

Bridging Formal and Informal Science Education

We used to consider science education to be exclusively school-based. This notion of science education has gradually become obsolete over the last few decades. The rapidly growing literature on students learning science in informal settings has unequivocally shown that students learn science outside schools as much as they do inside schools (Falk, 2001; Martin, 2004). Students encounter science outside schools at all times and in all forms. For example, television programs, both science-explicit and implicit in content, convey important scientific knowledge and ways of thinking. Weekend or summer visits to beaches, museums, and national parks provide learning opportunities for both school children and adults. Informal science educators call science learning outside schools free-choice science education (Falk, 2001). Free-choice science education is self-paced, voluntary, mostly free, non-sequential, and social; it takes place outside school and is facilitated by museums, science centers, print and electronic media, to name just a few. In any society, there exists a complex network of governmental and non-governmental institutions and programs that afford free-choice science education; they form free-choice science education infrastructure (Lewenstein, 2001). For example, 50% American adults read a daily newspaper, 53% watch one or more science TV shows each month, 60% visit a science museum at least once a year (National Science Board, 2008). With the popularization of the internet, more and more people are now seeking science related information from the internet (National Science Board, 2008).

Given the ubiquity of free-choice science education, it is necessary to bridge formal and informal science education and consider them as a continuum. For example, classroom science teaching should actively make use of free-choice science learning resources and opportunities by taking students for field trips or inviting guest speakers to the classroom. Similarly, workforce employees' continuing education may consider both on-site learning and formal courses offered at higher education institutions. Continuously improving science literacy in adults should be an integral component of human resources development in workforces.

Graduate Programs in Science and the Public

A science and the public notion of science literacy requires that all professionals are responsible for participating in science activities and at the same time promoting greater science literacy in the public. This requires that all professionals become both science participants and educators. The current science teacher education programs only educate school science teachers; it is necessary to educate science educators outside school to carry out the mission of science and the public. For example, research scientists, although they may be well equipped with current knowledge and skills in sciences, may not know how to communicate science to the general public. Medical doctors may be well prepared in dealing with patients, but they may not be well prepared for educating patients. Professionals with an undergraduate or graduate degree such as science reporters, government employees, museum staff, and so on, may have adequate initial education in sciences or other fields, but they may not possess current understanding related to such issues as science and religion, science and policy, science and humanism, science and secularism, etc; nor may they have adequate knowledge and skills in engaging in science education. There is a need for a graduate program to meet the above demand. Such a graduate degree program will enable professionals to upgrade their science knowledge and understanding; the program will also help these professionals develop knowledge and skills in conducting informal science education outside schools.

One example of the above science and the public graduate programs is the Ed.M. in Science and the Public (EdM SAP) at the State University of New York at Buffalo Launched in September 2006, the program is a 33 credit hours (9 courses + thesis), and offered completely online. The EdM SAP is designed to: (a) prepare professionals to better engage in public activities and debates related to science; (b) to promote science literacy and understanding in the public at large; and (c) to promote scholarship in science and humanism, science and public policy, and science in the political, religious and secular environments. All professionals with an interest in improving their own science literacy and in promoting the public understanding of science may apply. As of December 2008, there are close to 40 students enrolled in the program, and 5 have graduated with the degree. These students come from 15 US states, and 5 countries (US, Canada, Japan, Ireland & France). These students are professionals in various fields including research scientists and engineers, public relations officers, science film-makers, primary care pediatricians, freelance writers/editors, university professors, lawyers, veterinarians, school science teachers, and science museum educators. These professionals have a minimum of a bachelor's degree; some have more advanced degrees (e.g. MD, PhD, JD, DVM, MBA and MA). After graduating from EdM SAP, the hope is that they will become leaders in promoting the public understanding of science in their own professions.

Conclusions

Science literacy has traditionally been considered as a state to achieve or commodity to possess, in other words, as extrinsic to individuals. It has also been based on a deficit- and one-way informational flow model. However, achieving science literacy of this type has proven to be difficult by both the school population and the public. Improving science literacy requires reconceptualizing science literacy to be both a state and life-long process, as both a personal choice and an economic necessity, and as both a personal enhancement and civic participation. This new conception of science literacy implies that science literacy is a task of both formal and informal science education; it creates a demand for all professionals to become both science literacy participants and educators. In order to realize the above vision, there should be a perceived continuum between formal and informal science education. It is also necessary to educate science professionals in workforces to become science and the public educators, and improving science literacy should become an integral component of human resources development in workforces.

References

Aikenhead, G.S. (2006). *Science education for everyday-life: Evidence-based practice*. New York: Teachers College Press.

American Association for Advancement of Science. (1989). *Science for all Americans*. New York: Oxford University Press.

American Association for Advancement of Science. (1993). *Benchmarks for science literacy*. New York: Oxford University Press.

Apple, M.W. (1992). Do the standards go far enough? Power, policy, and practice in mathematics education. *Journal for Research in Mathematics Education, 23*(5), 412-431.

Baker, V. (2004). *Beyond appearances: Students' misconceptions about basic chemical ideas* (2nd ed.). London: Royal Society of Chemistry.

Bransford, J.D., Brown, A.L., & Cocking, R.R. (Eds.) (2000). *How people learn: Brain, mind, experience, and school*. Washington, DC: National Academy Press.

Bybee, R.W. (1997). *Achieving scientific literacy: From purposes to practices*. Portsmouth, NH: Heinemann.

Collins, A. (1998). National science education standards: A political document. *Journal of Research in Science Teaching, 35*(7), 711-727.

Council of Ministers of Education of Canada. (1997). *Common framework of science learning outcomes*. Toronto: Council of Ministers of Education.

DeBoer, G.E. (1991). *A history of ideas in science education: Implications for practice*. New York: Teachers College Press.

Department for Education and Employment. (1999). *The national curriculum for England.* HMSO.

Falk, J.H. (2001). *Free-choice science education: How we learn science outside school*. New York: Teachers College Press.

Friedman, T.L. (2006). *The world is flat: A brief history of the twenty-first century*. New York: Farr, Straus and Giroux.

Gabel, L.L. (1976). *The development of a model to determine perceptions of scientific literacy*. Unpublished doctoral dissertation, Ohio State University.

Garrson, J.W., & Lawwill, K.S. (1992). Scientific literacy: For whose benefit? In S. Hills (Ed.), *Proceedings of the second international conference on the history and philosophy of science and science education* (vol. 1, pp. 337-349). Kingston, ON, Canada: Queens' University Press.

Hand, B.M., Alvermann, D.E., Gee, J., Guzzetti, B.J., Norris, S.P., Phillips, L., Prain, V., & Yore, L.D. (2003). Message from the "Island Group": What is literacy in science literacy? *Journal of Research in Science Teaching, 40*(7), 607-615.

Hurd, P.D. (1958). Science literacy for American schools. *Educational Leadership,16*, 13-16.

Jenkins, E.W. (1997). Scientific and technological literacy: Meanings and rationales. In E. W. Jenkins (Ed.), *Innovations in science and technology education* (vol. 6, pp. 11-42). Paris: UNESCO.

Laetsch, W.M. (1987). A basis for better public understanding of science. In GIBA Foundational Conference (Ed.), *Communicating science to the public* (pp. 1-18). New York: John Wiley & Sons.

Lewenstein, B. V. (2001). Free-choice science infrastructure. In J. H. Falk (Ed.), *Free-choice science education: How we learn science outside of school*. New York: Teachers College Press.

Martin, L.M.W. (2004). An emerging research framework for studying informal learning and schools. *Science Education, 88*(suppl. 1), S71-S82.

Miller, J.D. (1987). Scientific literacy in the United States. In GIBA Foundational Conference (Ed.), *Communicating science to the public* (pp. 19-40). New York: John Wiley & Sons.

National Research Council. (1996). *National science education standards*. Washington, DC: National Academy of Sciences.

National Research Council. (2007). *Taking science to school: Learning and teaching science in Grades K-8*. Washington, DC: The National Academic Press.

National Center for Educational Statistics. (2006). *The Nation's report card: Science 2005*. Washington, DC: NCES.

National Science Board (2008). *Science and engineering indicators*. Arlington, VA: NSF.

Norris, S.P., & Phillips, L.M. (2003). How literacy in its fundamental sense is central to scientific literacy. *Science Education, 87*, 224-240.

Osborne, M.D., & Calabrese-Barton, A. (2000). Science for all Americans? Critiquing science education reform. In C. Cornbleth (Ed.), *Curriculum politics, policy, practice: Cases in comparative context* (pp. 49-75). Albany, NY: State University of New York Press.

Posner, G., Strike, K., Hewson, P., & Gertzog, W. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211-227.

Pintrich, P.R., Marx, R.W., & Boyle, R.A. (1993). Beyond cold conceptual change: The role of motivational beliefs and classroom contextual factors in the process of conceptual change. *Review of Educational Research, 63*(2), 167-200.

Roth, W.-M. (2002). Taking science education beyond schooling. *Canadian Journal of Science, Mathematics and Technology Education, 2*(1), 37-48.

Roth, W.-M., & Calabrese, A. (2004). *Rethinking scientific literacy*. New York: Routledge-Falmer.

Roth, W.-M., & Lee, S. (2004). Science education as/for participation in the community. *Science Education, 88*(2), 2630291.

Roberts, D.A. (2007). Scientific literacy/science literacy. In S. K. Abell, & Lederman, N. G. (eds.), *Handbook of research on science education*. Mahwah, NJ: Lawrence Erlbaum Associates, Publishers.

Shen, B.S.P. (1975). Science literacy and the public understanding of science. In S. B. Day (Ed.), *Communication of scientific information* (pp. 44-52). Basel, Switzerland: S. Karger A.G.

Shamos, M.H. (1995). *The myth of scientific literacy*. New Brunswick, NJ: Rutgers University Press.

Wandersee, J.H., Mintzes, J.J., & Novak, J.D. (1994). Research on alternative conceptions in science. In D. Gabel (Ed.), *Handbook of research on science teaching and learning* (pp. 177-210). New York: Macmillan.

Author

Xiufeng Liu is Associate Professor of Science Education and Director of the EdM in Science and the Public program. His research interests include learning progression of unified concepts, science curriculum policies, and technology-enhanced science assessment. **Correspondence:** Department of Learning and Instruction, Graduate School of Education, State University of New York at Buffalo, Buffalo, NY, USA. E-mail: xliu5@buffalo.edu