CHAPTER 2

The Literacies of Science

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One starting point for a dialogue between people in literacy education and science education is the way in which science uses multiple literacies. Literacy education usually begins with an emphasis on language and texts—how they are made and what they mean. Science education begins with questions about how things happen in the world. We might imagine a scientist studying literacy to be a bit like an ethnographer. An ethnographer of science and its literacies will encounter other scientists making and using texts but will look at the properties of texts only in relation to how they function in meaningful social and cultural activity.

What would our ethnographer see? Backs of envelopes with incomplete sketches, isolated words, a few lines of mathematical symbols, some arrows and question marks. Meticulous notebooks full of dates, columns, headings, and numbers. Shelves of textbooks, treatises, and handbooks. Piles of offprints, preprints, reprints, and printouts. People talking while jotting down formulas or sketching diagrams on whatever is at hand: a blackboard or whiteboard, a pad of paper, the back of an envelope, a napkin. People entering numbers in notebooks while adjusting dials and tilting their heads at funny angles. People sitting silently at computer screens filled with numbers, graphs, and bizarre visual displays, making little notes on pads of paper. And once in a great while, someone sitting at a keyboard and creating complete sentences of English, neatly arranged into paragraphs and separated by lines of mathematical symbols, tables of numbers, graphs of crooked lines, diagrams of apparatus, or more unusual visual displays.

Scientists often say that mathematics is the language of science, but it would be closer to the whole truth to say that the language of science is a unique hybrid: It is natural language as linguists define it, extended by the meaning repertoire of mathematics (the set of possible meanings that can be made with mathematical symbols and the conventions for interpreting them), contextualized by visual representations of many sorts, and embedded in a language (or, more properly, a semiotic) of meaningful, specialized actions afforded by the technological environments in which science is done. The texts of science are not written in any natural language studied by

linguists. They are written in as much of this hybrid meaning-making system as can be presented on paper or animated on a computer screen.

Why? Is the use of these other semiotic media just a convenience, or is it a shortcut? Could we conduct science entirely with words? Not begging the question by counting every mathematical expression as some sort of word, the answer, pretty clearly, is no. And herein lies the heart of what I believe science has to say to literacy: Some meanings cannot be made with natural language, and natural language itself is an artificial notion, detached for academic and disciplinary reasons from the whole of embodied human communication. Human beings always do make meanings that go beyond the limitations of natural languages. Our biology and our survival in a material environment require us to do so. The *world* makes meanings that go beyond what natural language can say: Our proteins and cells and their membranes do, organisms of other species do, ecosystems do, and cosmology does. Science is the great enterprise of paying attention to the kinds of meanings that require us to go beyond natural language. Its weakness is that it sometimes has become so preoccupied with these meanings that it has forgotten that it also does use natural language, but natural language is not a tool whose properties it knows how to take into account. Science also sometimes excessively idealizes the systems it studies, never more so than when it forgets to take into account that scientists, as human beings themselves, are necessarily a part of every system of which we can have human knowledge.

I want to raise some questions here about the literacies of science and why they are what they are. I want to encourage science educators not only to study how teachers and students read, write, and talk science but also to learn more about how and why scientists do so, and to share with colleagues in literacy education the unique insights into the nature of literacy practices and literate texts that come from the perspective of science.

Meaning by Kind and Meaning by Degree

The whole of meaning—the whole of communication—is an evolved human capacity for survival in a physical and biological world. The whole of communication includes gestures and posture, facial expressions, mime, nonverbal vocalizations, drawings, and a great deal more. What can you communicate with a gesture that you cannot say in words? What can you represent with a drawing or a map that cannot be said? Even speech itself is more than just language: we vary the timbre and pacing of our voices and the sharpness and force of our articulation in ways that convey emotion, mood, health, seriousness, importance, urgency, surprise, doubt, need, desire, and

a host of other core human meanings essential to social cohesion and group survival. In all these cases, we make meaning into a matter of degree.

Before the mathematics of a continuum (the infinity of points on a line), before any understanding of real numbers (e.g., 3.14159268 or *pi*), there was geometry—lengths and areas, ratios of lengths and areas, angles, and the Pythagorean irrational lengths (e.g., one side of a triangle that is square root of 2 inches long). Verbal mathematics began with the whole numbers, but visual mathematics never was limited to discrete values (one versus two versus three) and whole-number ratios ($^1/_2$, $^2/_3$, $^5/_6$, etc.). Verbal language was extended early on first from the whole numbers to unit fractions ($^1/_2$, $^1/_3$, $^1/_4$, $^1/_5$, etc.) and then to multiples of unit fractions, but only visual displays really could convey the holistic meaning of a nonsimple ratio (e.g., $^7/_{13}$). Visual displays can freeze into place what from time immemorial has been a function of bodily gesture and posture. How low do you bow? How firmly do you shake hands? How wide do you open your eyes? How soon do you respond? How close do you stand? At what angle do you raise your arm to point?

There are no names in natural language for all the angles from acute to obtuse. There is hardly any way in formal verbal language to express subtle differences of degree or ratio. There is no way to describe the shape of a mountain, cloud, or face or to describe precisely the twists and turns of a winding path. There are no words to distinguish degrees of speed or trajectories of motion. There are no words for *all* the intervals of time that matter in life. We can say "three seconds" or "three millennia" but without mathematics we cannot say 1.3758 seconds or 358,000,000,000 years, and even words like *seconds* and *millennia* (or *billions*) come to us from very old mathematics. There are not nearly enough words for all the degrees of certainty and doubt, importance and urgency, unexpectedness and surprise, or need and desire that matter to us. Why?

Linguistics does understand one part of human communication—not all of speech, nor even all of writing, but the ways in which discrete words combine to make vast numbers of possible meanings (yet always a finite number of them) and the ways in which discrete words are distinguished from one another by being composed of discrete classes of sounds. An infinite continuum of possible vocal articulations exists, but every linguistic community divides it arbitrarily into a relatively small number (less than 100, usually) of discrete sound zones. Speakers learn to keep away from the fuzzy borders between zones. Words are distinguished from other words not by subtle acoustic degrees of difference but by systematic contrasts

between sounds in different zones—for example, *pat* or *pot* or *pit*, *pat* or *bat* or *fat*, or *pat* or *pad* or *pack*. Words do not blend into one another; they do not form a continuum, and neither do the meanings that natural language enables us to make with combinations of words. Every phrase, clause, and sentence stands in systematic contrast with a very large number of other related phrases, clauses, and sentences—for example, *a big man*, *a little man*, *a big dog*, *one big man*, or *the big man*. In grammar, a verb can be present or past tense, but there is no continuum or degree of tenses in between. We can speak in first person or third person, but there is no intermediate continuum of modes of address.

Natural language does have some resources for expressing matters of degree, but they are only discrete points of reference in the continuum (e.g., words such as *small*, *little*, *tiny*, *microscopic*, and *infinitesimal*). Natural language recognizes that not all things come in discrete, countable units—for example, one dog, two dogs, or three dogs. We can have one jar of water or two, but not two waters (except metaphorically for two bodies of water), and water is the sort of thing that can fill a jar to any possible degree. Named units of measure came historically long before the concept of measure, which in turn could not exist before the expression of arbitrary fractions of a unit. The concept of an amphora (big jug) of wine (one amphora, seven amphoras) came before the concept that any amount of wine could be measured as some number of amphora units (e.g., .85 amphoras, 123 and $^{7}/_{16}$ amphoras, etc.). The concept of a "unit of measure" is difficult even for many students today, once we take it beyond common phrases in natural language. It is not even a concept shared in all cultures (Verran, 2001). Of course, people measured things and recognized the concepts of length, weight, area, volume, and so on. It was the measurement of real objects that led to the need for unit fractions and multiples of unit fractions. It was the comparison of such measures that led to non-simple ratios, and the most basic natural comparison was the geometric angle. Natural language was extended to speak of fractions, and the arithmetic of the closed ring of rational numbers began (all whole numbers and fractions). Geometry begins with scale drawing for surveying, maps, and architecture. Perhaps scale drawings or shadow ratios and plumb lines were used even before there was a way to name in mathematical words the length of a line; certainly they were used before there was a way to name areas or volumes ("square miles," "cubic feet").

The natural world, both materially and socially, is about both *kinds* and *degrees*. Animal and plant species come in discrete kinds. Humans artificially divide themselves into discrete kinds (e.g., tribes, races, and nations).

Natural language abets the creation of artifacts that are of discrete kinds. It also abets the creation of concepts that are discrete and often contrasting (e.g., beauty and ugliness, good and evil, horizontal and vertical, and mass and weight). However, between horizontal and vertical, for example, there is only one concept (i.e., oblique or angled) but an arbitrarily large number of realities and meanings that need to be distinguished for practical purposes. What matters to humans about material phenomena very often is a matter of degree rather than kind—size, shape, speed, rate, height, weight, density, composition, tensile strength, salinity, acidity, and so on. And the great discovery on which science is based is that there are mathematical regularities in the relations among these quantities of degree. Indeed, mathematics largely was developed to describe just these empirical relationships—constant ratios, linear proportionalities, geometrical means, quadratic and cubic ratios, and additivities.

Early mathematics grew out of practical activity. It was not a formal and systematic field but an artisanal craft, built of rubrics and algorithms and very often made sense of through diagrams that were abstracted from drawings of real situations. People solved practical problems that required them to use meaning-by-degree as well as meaning-by-kind through a combination of natural-language concepts, gestures, technological artifacts and the practices of using them, measurements, drawings, abstract diagrams, and mathematical tables and procedures. In their origins and functions, these precursors of the hybrid meaning resources of modern science were already interdependent. And so they remained for most of their histories. Mathematics frequently branched off as an abstract study, but until the 20th century, most of its conceptual advances came from work on scientific and technological problems. Long before Descartes made coordinate geometry the basis for a homology between graphs and algebraic equations, equations were translated into numerical tables and diagrams of the results were presented in forms that look very much like our modern scientific data graphs. Early numerical tables were constructed linguistically as much as visually: Every row was a complete sentence of Latin, with numbers inserted before nouns. Abstract diagrams owed as much to schematic drawings as to geometrical forms: Bernoulli calculated the forces exerted by muscles on bones at various angles of the joints using Newtonian mechanics and geometrical diagrams of angles and forces abstracted from schematic drawings of the human skeleton. Galileo inserted a tiny drawing of Saturn, with the rings that he first saw in place of the word *Saturn* in a line of written text.

Science learned to combine meaning-by-kind and meaning-by-degree, and throughout its history these two modalities have influenced one another so that today the concepts and communications of science fuse them inseparably. Scientific text embodies this fusion. *Scientific literacy is not just the knowledge of scientific concepts and facts; it is the ability to make meaning conjointly with verbal concepts, mathematical relationships, visual representations, and manual-technical operations.*

Multimodal Literacy in Science: Texts and Classrooms

In one recent study (Lemke, 1998), I examined the semiotic forms found in the standard genres of research articles and advanced treatises of professional scientific publications. In a diverse corpus, across disciplines and publication venues, the clear finding was that there usually is at least one, and often more than one, graphical display and one mathematical expression per page of running text in typical scientific print genres. There easily can be three or four each of graphics displays and mathematical expressions *per page*, separate from verbal text.

In one prestigious journal of the physical sciences, each typical three-page article integrated four graphical displays and eight set-off mathematical expressions. Other articles had as many as three graphical displays per page of double-column text or as many as seven equations per page. In another journal, one in the biological sciences, each typical page had two nontabular visual-graphical representations integrated with the verbal text, and each short article, with an average length of 2.4 pages, typically had six graphics, including at least one table and one quantitative graph.

To appreciate the absolutely central role of these nonverbal textual elements in the genres being characterized, it may help to ponder a few extreme (but hardly unique) cases that follow:

- In one advanced textbook chapter, a diagram was included in a footnote printed at the bottom of the page.
- In one seven-page research report, 90% of a page (all but five lines of main text at the top) was taken up by a complex diagram and its extensive figure caption.
- The main experimental results of a 2.5-page report were presented in a set of graphs occupying one-half of a page and a table occupying

three-fourths of another. The main verbal text did not repeat this information but only referred to it and commented on it.

- In most of the theoretical physics articles, the running verbal text would make no sense without the integrated mathematical equations. These could not, in most cases, be effectively paraphrased in natural language, even though they can be, and are normally meant to be, read as part of the verbal text (in terms of semantics, cohesion, and, frequently, grammar).

A more detailed analysis in this study showed how absolutely normal and necessary it is to interpret the verbal text in relation to these other semiotic formations, and vice versa. They are not redundant, each presenting the complete relevant information in a different medium; rather, the nature of the genre presupposes close and constant integration and cross-contextualization among semiotic modalities.

In a recent analysis of videotape data of one student, John, going through a day of advanced chemistry and physics classes (Lemke, 2000; see also Cumming & Wyatt-Smith, 1997), I observed that in his chemistry lesson, John had to interpret the following:

- A stream of rapid verbal English from his teacher
- The writing and layout information on an overhead transparency
- Writing, layout, diagrams, chemical symbols, and mathematical formulas in the open textbook in front of him
- The display on his hand-held calculator
- Writing, layout, diagrams, symbolic notations, and mathematics in his personal notebook
- The teacher's gestures, blackboard diagrams, and writing
- The actions and speech of other students, including their manipulation of demonstration apparatus
- The running commentary of his next-seat neighbor

In fact, John quite often had to integrate and coordinate most of these semiotic modalities either simultaneously or within the span of a few minutes. He could not have kept up with the content development and conceptual flow of these lessons without integrating at least a few of these different semiotic modalities almost constantly.

In one episode during the physics lesson, there was no use of the notebook and no diagram, just a pure interaction of language and gestural pantomime, including whole-body motion. The teacher, Mr. Phillips, was standing just in front of the first (empty) row of student desk tables at the opposite end of the room from where John was sitting. John saw his teacher's hands cupped together to form a sphere, then the hands moved a foot to the left and cupped together to make another sphere. Then, they moved back to the first position, and one hand and Mr. Phillips's gaze made a sweeping gesture from one position in space to the other. Next, Mr. Phillips began to walk to the left, repeating these gestures and walking down toward John's end of the room. Fortunately, Mr. Phillips also was talking, so by integrating the teacher's precise and conventionalized mime with his accompanying technical speech, John could interpret that the cupped hands were atoms and the sweeping hand was a photon emitted by the first atom that traveled to the second, was absorbed there, and was reemitted after a while to pass down, atom by atom, through a ruby crystal, producing a "snowball effect" of more and more photons of exactly the same energy. In other words, the crystal was a laser.

Then, Mr. Phillips said he was going to add more complexity to the picture. An atom "might shoot out a photon in this direction," he said as he gestured away from the axis of the room-sized imaginary ruby crystal and toward the students, "Or in this one," he said as he gestured back toward the blackboard, "Or...," he said as he made an oblique gesture. "How do we get a laser beam, then?" He walked back and forth between the ends of his now-lasing, imaginary ruby crystal, describing the mirrors that he gestured into imaginary being at each end, saying that the mirrors differed in reflectivity and transmissivity to build up and maintain the avalanche of photons while letting some photons out in the form of the laser beam.

John had seen pantomimes such as this before; he also had seen diagrams of atoms and crystals and of photons being absorbed and emitted by atoms. He was able to use the visual literacy of these past diagrams, together with his literacy in pantomime and his verbal discourse literacy in atomic physics, to synthesize a model of how a laser works.

John was lucky. He appeared to have the required literacies and ability to combine and synthesize them across media, events, and semiotic modalities. There was a great deal that John already had to know in order to make sense of what he was learning in these lessons from minute to minute—not just language and verbally expressed discourse formations (such as the intertextual thematic formations I have described in Lemke [1990, 1995] and

elsewhere), but conventional diagrams of atomic arrangements in a crystal, standard graphs of atomic energy levels, typical ways of gesturing to show directionality in space, and common notations for the algebraic and symbolic representation of chemical reactions and stoichiometric calculations of concentrations and the pH of solutions. His literacy extended to motor routines in operating a calculator, social discourse routines of question and answer in a classroom, and technical practices in manipulating a spectroscope and diluting a solution. He constantly had to translate information from one modality to another—numerical to algebraic, algebraic to graphical, graphical to verbal, verbal to motor, pantomime to diagrammatic, and diagrammatic to discursive. But simple translation is not enough; John had to be able to integrate multiple media simultaneously to reinterpret and recontextualize information in one "channel" in relation to that in the other channels, all to infer the correct or canonical meaning on which he would be tested. In most such cases with students, the complete meaning in a science lesson or text is not expressed by using only one channel, but only when using two or more or even all of them taken together (see detailed examples in Lemke, 2000; Roth, 2002; Roth & Bowen, 1999; Wells, 2000).

Implications for Science and Literacy Education

The implications of these semiotic facts about scientific literacy for science education seem fairly obvious: We need to devote more explicit attention to teaching students how to read hybrid text. We need to help them understand the conventions that connect verbal text with mathematical expressions and graphs and diagrams of all kinds. We need to help them reproduce the fusion of conceptual kinds and quantitative degrees that is central to scientific meaning-making by giving them practice in translating back and forth among verbal accounts, mathematical expressions and calculations, schematic diagrams, abstract graphs, and hands-on actions. In many cases, teachers can expand their own teaching repertories by making more use of gestural and visual representations and numerical tables and simple graphs, even before students are ready for more formal mathematical expressions. Students need not only to do hands-on science and talk and write science in words; they also need to draw, tabulate, graph, geometrize, and algebrize science in all possible combinations.

But what does this view from science education have to say to the wider field of literacy education? Is this multimodal, hybrid language of science special and unique and of no relevance to literacy education in general? Or does it point to a broader, more ethnographic approach to all of literacy—

one that situates word meanings in the larger context of students' visual and cultural experience? One that fuses verbal and visual literacy back together again across the widest range of genres and insists that students learn to write as well as read multimodally in every subject area?

Cultural historians have written much in recent decades about the logocentrism of modern academic traditions. Contemporary cultural theorists have been impressed by the "visual turn" in the meaning-making habits of first the television generation and now the Internet generation. Open any magazine or view any website, and you will see how rich are the complex hybrids and fusions of visual and verbal meaning resources. They have more in common with scientific articles and textbooks than they do with the pure verbal text of traditional literacy. Scientific and technical disciplines today are leading the way in incorporating animations, dynamic simulations, and video in the explication of research questions. Websites are becoming full multimedia presentations, including interactive dynamic media, audio, video, and animation for all subject areas. CD-ROMs, although only a transitional technology, display the future of the Web in these respects. Immersive environments, whether of the virtual-reality type or akin to the existing multiplayer online gaming environments, are the next stage in this evolution.

Text is becoming more and more integrated into multimedia. Purely textual literacy will survive, but it will not continue to hold the dominant place that it has in the past. Students in all subjects need to know how to critically interpret and analyze video and animations, schematic drawings and diagrams, and other visual resources in relation to verbal text, and vice versa. All of literacy education has a great deal to learn from scientific literacy, which was long ago the pioneer of this multimodal fusion.

To teach the literacies of science well, science educators need to create partnerships with verbal literacy educators and with visual media educators. I hope I have at least suggested in this chapter why such a partnership would be mutually beneficial for us all.

What Literacy Education Has to Say to Science Educators

Although I began my career as a physicist and science educator, I also have worked in the area of literacy education, particularly on its theoretical foundations in the fields of text semantics; discourse analysis; genre structure; rhetorical analysis; and the study of academic, bureaucratic, and scientific

language. As coeditor of the international research journal *Linguistics and Education*, I have had a wide overview of research relevant to literacy education.

There are a number of trends and developments in literacy education research to which science educators would do well to pay attention. I want to identify just a few of these in the following list:

1. **The role of social dialect and community culture in students' writing and their interpretation of texts.** Literacy educators today are acutely aware of the divergences between home and school language for many students, and also of the differences in attitudes, values, and priorities of students' home and peer cultures relative to those of the school and its curricular areas. Science educators need to be aware of issues in science learning that are associated with speaking English as a second language, writing standard English for speakers of nonstandard dialects, and coming from home communities that may not agree with the secular value system of modern science as a culture.
2. **Research on students' language and literacy experiences outside the school.** Science education seems implicitly to assume that students' only relevant exposure to science is through the school curriculum. There is very little systematic research on students' reactions to science as portrayed in various popular media or to their experience with various forms of technology in daily life (including medical and pharmaceutical technologies).
3. **"Across the curriculum" approaches to multiplying the effects of language arts instruction.** To some extent, mathematics educators have tried to follow this lead, but "science across the curriculum" is a notion that seems to exist at best in sporadic efforts in specialized schools. If science would define itself somewhat more inclusively—to include all of technology and the social, ethical, and political issues arising from the applications of science in the contemporary world and at least a partial claim on the history of science and technology and the interpretation of literature and media that address issues of science and technology—then "science across the curriculum" could be a powerful means to engage students and sustain their engagement with scientific thinking.

A Note on Gender Issues

In preparing an initial dialogue for the Crossing Borders: Connecting Science and Literacy conference (a set of remarks that served as the basis for this

chapter), Donna Alvermann (see chapter 12) and I were well aware of the gender implications of giving a male voice to science and a female voice to literacy in the dialogue. Historically, both literacy and science—indeed, all public academic knowledge and standing—were reserved for males. This restriction was not accidental, nor even an inheritance from time immemorial. It was created by the repeated work of generations, against resistance, and despite briefer and longer historical periods in which women's rights to participation in the world of public knowledge were effectively maintained against perennial opposition. The story, at least for Europe and the United States, is a fascinating, enlightening, and appalling one (see David Noble's [1992] book *A World Without Women* for one male historian's version).

But literacy—in private, and later in public—was attained by women long before they succeeded to any significant degree in opening up the institution of science to their full participation. In education, women have taught literacy in significant numbers for a very long time; they have only recently come, and still in relatively small numbers, to the teaching of science. The teaching of literacy has been associated with primary education, and so with women's traditional role in the education of children. The teaching of science until very recently has been limited to adolescents and adults. Women are far more than proportionally represented among literacy researchers and far less than proportionally among science education researchers.

The legacy of history lives still. Female graduate students in the "hard" sciences still report feeling excluded from a world of masculine camaraderie. But the deeper, still largely unanswered question is this: How have centuries of male domination and female exclusion affected the intellectual structure of science itself as a discipline? It is very clear that male scientists do still try to perform a masculine gender identity (cf. Butler, 1993) through their scientific activities. Male scientists are disposed to "hard data," "tough-minded argument," and an adversarial approach to resolving conflicting scientific claims. They admire risk-taking in general and manual dexterity in the laboratory. They form hierarchical research groups led by an "alpha male." They respect abstract and quantitative argumentation for their own sake. They swagger and intimidate and are admired by other males for doing so.

Traweek (1988) describes this scientific culture and its effect on female students. Walkerdine (1990) looks at the masculinization of scientific forms of rationality. It is more difficult for female scientists to perform a feminine gender identity through the same practices, and it is likely that the practices themselves will have to change or be expanded, even as the nature of gender identities in our society changes (cf. Walkerdine, 1990).

Correspondingly, has literacy education and its study and research become at all "feminized" in recent generations, either in its practices or in its academic image?

Are the dialogues of literacy education and science education significantly gender dialogues? Do my proposals that we refocus literacy education to include multimedia and multimodal literacies, including mathematics and formal abstract representations and with a computational technological base, tend to shift the gendering of literacy and literacy education toward the masculine pole? Would such a shift tend to put off younger female researchers and attract more male researchers?

Should we take special care to open the door also to more artistic and aesthetic modes of visual and verbal representation and to greater emphasis on social relationships and collaborations? Cultural divisions by gender may be mostly arbitrary and sometimes rather foolish, especially in their stereotypes, but they also are all too often quite real and socially pervasive. No institution in our society is immune; no practice with a long history avoids shaping by dead hands. Only critical vigilance, and dialogues not only between science educators and literacy educators but also among people of the widest variety of gender identities, will make our own contributions to this history progressive ones.

Some Further Areas for Collaboration

There are three other thematic areas in which I think one could explore fruitful dialogue between science and literacy educators.

First, we ought to examine together the criteria for what counts as sophisticated and critical literacy for scientific-technical, literary, and popular media texts, chipping away at false dichotomies that make reading literary and scientific texts seem serious and reading popular media texts seem frivolous. Intelligent and critical reading has many common features, regardless of the genre or register (i.e., specialized discourses) of texts, and we need more systematically to identify and encourage these features of thoughtful reading so students can bring them to bear on all kinds of texts. How they choose to read depends on the context of the activity and their current agendas, but even this can surprise us because people can be serious and critical even in their leisure activities.

Students who excel at reading in one register or genre either may not choose to read other texts as carefully or may not know how to do it. It is also important for educators from both science and literacy fields to define what counts as sophisticated reading for scientific texts and to define the relation

between critical reading of expository text and critical analysis of data, argumentation, and evidence. I think we educators will find that we all have a lot to say to one another about these issues.

A second thematic area is that of literacy and identity issues: How do students perform their various identities in the medium of popular culture, and what space is there for linkages between their identity development and school culture, including "serious" literature and science? If education means helping students make a transition from only participating in local worlds and communities to knowing how to participate in more diverse worlds and larger communities, then how do we build bridges between what they are doing with popular media and who they are and who they imagine they could become? This is a very crucial issue for science educators because the stereotypical way in which science presents itself so often is at odds with the kinds of identities students, especially adolescents, want to perform.

Finally, there is a large body of literature written by outstanding scientists, mathematicians, and engineers attesting to the key role of intuition, aesthetic sensibility, and playfulness in scientific and mathematical creativity (e.g., Tauber, 1996; Wechsler, 1981). Too often, science presents itself only in terms of the results of research and does not say much about the process itself. When it does address process, there is an overemphasis on the straight and narrow, hard-work, highly technical, controlled, and systematic processes of research—to the neglect of the more creative and intuitive aspects of scientific inquiry, which are precisely the ones for which connections to adolescent identity potentially can be made. Research on identity and adolescents' engagement with literature and with their own writing should provide helpful guidance to a science education program that is serious about the humanistic side of real scientific work.

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