

The Literacies of Science

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One starting point for a dialogue between literacy education and science education is the way in which science uses multiple literacies. Literacy education usually begins with an emphasis on language and on texts: how they're made, 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 come across 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.

This paper was first conceived as part of an extended dialogue between themes in science education and in literacy education, two fields in which I have worked over the years. At various points I was writing, prospectively and then retrospectively, in relation to a complementary paper by Donna Alverman. I have put the most dialogical parts in two sections at the end of the paper, placing my main argument first where it can stand on its own for readers who may not have access to the whole volume, which presents many connections between science and literacy education (Crossing Borders, ed. E. Wendy Saul, 2004).

The most important thing that science and science education have to say to literacy educators is, I think, that language and discourse are embedded in our practices in the material world and do not easily make sense except in these contexts, especially when we are first learning them (cf. Gee 19..). This perspective is especially salient in science because we use language only in coordination with many other modes of semiotic representation: visual images, diagrams, graphs, mathematical formulas, and the semiotics of artifacts, apparatus, and the meaningful activities of using them. Scientific communication and scientific literacy are fundamentally multimodal; they call for a critical multimedia literacy that is not limited to text or language in its narrowest sense. It seems likely that science is not unique in this respect, and that literacy education can contribute in important ways not just to improving how we read and write science, but also to more comprehensively understanding how we make meaning in all fields.

This theme is one starting point for dialogue between literacy and science, but there are many others, and I discuss some of those more briefly at the end of this paper.

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, numbers. Shelves of textbooks, treatises, and handbooks. Piles of offprints, pre-prints, re-prints, and print-outs. People talking while using a whiteboard like the back of an envelope. 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 or tables of numbers or graphs of crooked lines or diagrams of apparatus or more unusual visual displays.

It is often said, by scientists, 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: natural language as linguists define it, extended by the meaning repertoire of mathematics, 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, just a short-cut? *Could we conduct science entirely with words?* Not begging the question by counting every mathematical expression as some sort of 'words', the answer pretty clearly is *No*. And here 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, 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, our cells and their membranes do; organisms of other species do; ecosystems do; 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 has sometimes become so pre-occupied with these meanings that it has forgotten that it does also use natural language, but that natural language is not a tool whose properties it knows how to take into account. Science also sometimes excessively idealizes the systems it studies, nowhere moreso than when it forgets to take account that scientists as human beings 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 just 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 our 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 is more than language: we vary the timbre and pacing of our voices, 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 core human meanings essential to our social cohesion and group survival. In all these cases, we make meaning about matters of degree.

Before the mathematics of the continuum, before any understanding of real numbers, there was geometry. Lengths and areas, ratios of lengths and areas, angles, and the Pythagorean irrational lengths. Verbal mathematics began with the whole numbers, but visual mathematics was never limited to discrete values and whole number ratios. Verbal language was extended early on from the whole numbers first to unit fractions and then to multiples of unit fractions, but only visual displays could really convey the holistic meaning of a nonsimple ratio. Visual displays freeze in 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 of ratio. There is no way to describe the shape of a mountain or a cloud or a face. No way to precisely describe 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. There are not nearly enough words for all the degrees of certainty and doubt, importance and urgency, unexpectedness and surprise, 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. Just the ways in which discrete words combine to make vast numbers of possible meanings, but always a finite number, always a countably finite number. Just the ways in which discrete words are distinguished from one another by being composed of discrete equivalence classes of sounds. There is a continuum infinity of possible vocal articulations, but every linguistic community divides it arbitrarily into a relatively small number (less than a hundred 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. Pat or pot or pit. Pat or bat or fat. Pat or pad or pack. *Words do not blend into one another; they do not form a continuum.* And neither do the meanings natural language enables us to make with combinations of words. Every phrase, every clause, every sentence stands in systematic contrast with a very large number of other agnate phrases, clauses, and sentences. A big man. A little man. A big dog. One big man. The big man. In grammar, a verb can be present tense 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 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 like *small, little, tiny, microscopic, infinitesimal*). Natural language recognizes that not all things come in discrete countable units (one dog, two dogs, 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 could not exist before the expression of arbitrary fractions of a unit. 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 nonsimple 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. Geometry begins with scale drawing, for surveying and for maps and for 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 before there was a way to name areas or volumes.

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 (tribes, races, nations). Natural language abets the creation of artifacts which are of discrete kinds. It also abets the creation of concepts which are discrete and often contrasting (beauty/ugliness; good/evil; horizontal/vertical; mass/weight). And yet between horizontal and vertical there is only one word (oblique, 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 is very often a matter of degree, rather than kind: size, shape, speed, rate, height, weight, density, composition, tensile strength, salinity, acidity, etc. And the great discovery on which science is based is that there are *mathematical regularities in the quantitative relationships among these quantities of degree*. Indeed mathematics was largely 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 formal and systematic, 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, measurement, 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 with one another. And so they remained for most of their histories. Mathematics frequently branched off as an abstract study, but most of its conceptual advances until the 20th century 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 presented in forms that look very much like our modern scientific data graphs. Early numerical tables were constructed as much linguistically 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 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 so influenced one another 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 publication. In a diverse corpus, across disciplines and publication venues, the clear finding was that there is typically 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 can easily be 3-4 each of graphics displays and mathematical expressions separate from verbal text *per page*.

In one prestigious journal of the physical sciences, each typical 3-page article integrated *four* graphical displays and *eight* set-off mathematical expressions. Some had as many as three graphical displays per page of double-column text, or as many as seven equations per page. In another journal, in the biological sciences, each typical page had two non-tabular visual-graphical representations integrated with the verbal text, and each short (average length 2.4 pages) article typically had six graphics, including at least one table and one quantitative graph.

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

- In one advanced textbook chapter, a diagram was included in a footnote printed at the bottom of the page.
- In one 7-page research report, 90% of a page (all but 5 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 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, which could not in most cases be effectively paraphrased in natural language, even though they can be, and are normally meant to be read out as if 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. It is not the case that they are 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 following one student through a day of advanced chemistry and physics classes (Lemke 2000, see also Cumming & Wyatt-Smith 1997), I observed that in his chemistry lesson this student had to interpret:

- 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 handheld calculator;
- more writing, layout, diagrams, symbolic notations, and mathematics in his personal notebook;
- observations of gestures and blackboard diagrams and writing by the teacher;
- observations of the actions and speech of other students, including their manipulation of demonstration apparatus, and
- the running by-play commentary of his next-seat neighbor.

In fact he had quite often to integrate and co-ordinate most of these either simultaneously or within a span of a few minutes. There is no way he could have kept up with the content development and conceptual flow of these lessons without integrating at least a few of these different literacy modes almost constantly.

In one episode in the physics lesson, there is no role for the notebook, and not even a diagram, but a pure interaction of language and gestural pantomime, including whole-body motion. The teacher, Mr. Phillips, is standing just in front of the first (empty) row of student desks, at the opposite end of the room from where the student, John, is sitting. John sees his teacher's hands cupped together to form a sphere, then the hands move a foot to the left and cup together to make another sphere. Then back to the first, and one hand and Mr. Phillips' gaze make a sweeping gesture from one to the other; then Mr. Phillips begins to walk to the left, repeating these gestures and walking down toward John's end of the room. Fortunately, Mr. Phillips is also talking and John is not deaf; by integrating the teacher's precise and conventionalized mime with his accompanying technical speech, John can interpret that the cupped hands are atoms, the sweeping hand a photon, emitted by the first, traveling to the second, absorbed there, re-emitted after a while, passing on down through a ruby crystal, producing a "snowball effect" of more and more photons of exactly the same energy. In other words, the crystal is a laser.

Mr. Phillips says he's going to add more complexity to the picture now. An atom "might shoot out a photon in this direction" -- gesture away from the axis of the room-sized imaginary ruby crystal toward the students -- "or in this one" -- gesture back toward the blackboard -- "or ..." -- oblique gesture. How do we get a laser beam then? He walks back and forth between the ends of his now lasing, imaginary ruby crystal, describing the mirrors he gestures into being at each end, but saying they differ in reflectivity and transmissivity, to build up and maintain the avalanche of photons, while letting some out in the form of the laser beam.

John has seen mimes like this before; he has seen diagrams of atoms and crystals, of photons being absorbed and emitted by atoms. Intertextually, he can 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 is lucky. He does appear to have the required literacies, and to be able to combine and synthesize them across media, events, and semiotic modalities. There is a great deal that John must already know in order to make sense of what he is learning in these lessons minute to minute. Not just language and verbally expressed discourse formations (such as the intertextual thematic formations I have described in Lemke 1995 and elsewhere), but conventional diagrams of atomic arrangements in a crystal, standard graphs of energy levels of atoms, typical ways of gesturing 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 extends 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 must constantly translate information from one modality to another: numerical to algebraic, algebraic to graphical, graphical to verbal, verbal to motor, pantomime to diagrammatic, diagrammatic to discursive. But simple translation is not enough; he must be able to integrate multiple media simultaneously to re-interpret and re-contextualize information in one channel in relation to that in the other channels, all in order to infer the correct or canonical meaning on which he will be tested. In most

cases, the complete meaning is not expressed in any one channel, but only in two or more, or even only in all of them taken together (see detailed examples in Lemke 2000, Roth & Bowen 2000, Wells 2000).

Implications for Science Education 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 with 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 we can expand our own teaching repertoires 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 to not just do hands-on science and talk and write science in words; they also need to draw science, tabulate science, graph science, and geometrize and algebraize 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-meaning 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 of 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 then the 'internet generation'.

Open any magazine, 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 existing massively multi-player online gaming environments are the next stage in this evolution.

Text is becoming more and more totally integrated into multimedia. Purely textual literacy will survive, but it will not continue to hold the dominant place 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 here 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 have also worked in the area of literacy education, and 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 co-editor 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 which science educators would do well to pay attention to. I want to identify just a few of these:

(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 and values and priorities of students' home and peer cultures relative to those of the school and its curriculum areas. Science educators need to be aware of issues in science learning that are associated with speaking English as a second language, with writing standard English for speakers of nonstandard dialects, and with coming from home communities which may not agree with the secular value system of modern science as a culture.

(2) *Research on the language and literacy experiences of students outside the school.*

Science education seems to implicitly assume that students' only relevant exposure to science is through the school curriculum, and 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 all of the social, ethical, and political issues arising from the applications of science in the contemporary world, and to include at least a partial claim on the history of science and technology and the interpretation of literature and media which 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 Issues of Gender

Historically, both literacy and science, indeed all public academic knowledge and standing was reserved to males. Nor was this accidental, nor even an inheritance from times 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 U.S. is a fascinating, enlightening, and appalling one (see David Noble's 1992 *A World Without Women* for one male historian's version).

But literacy, in private, and then in public was gained by women long before they succeeded to any significant degree in opening up the institutions of science to their full participation. In education, women have taught literacy in significant numbers for a very long time; they are 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 has till very recently been reserved to adolescents and adults. Women are far more than proportionally represented among literacy researchers, and far less than proportionally among science education researchers.

The work of history lives still. Female graduate students in the 'hard' sciences still report feeling left out of a world of masculine camaraderie. But the deeper question, still largely unanswered, 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 through their scientific activities. 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 gendered identities in our society changes.

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 gendered dialogues? Do my proposals that we re-focus 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 esthetic 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 are also 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 among people of the widest variety of gender identities, will make our own contributions to this history progressive ones.

Some Further Zones for Collaboration

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

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 features in common, regardless of genre or register of texts, and we need to more systematically identify and encourage these features, so students *can* bring them to bear on all kinds of texts (what they *choose* to do depends on the context of activity and their current agendas, but even this can surprise ... we can be serious and critical even in our play). Students who excel at reading in one register or genre may either not choose to read other texts as carefully or may not know how to. It is also important for educators from both science and literacy fields to define what counts as sophisticated reading for scientific texts, and the relation between critical reading of expository text and critical analysis of data, argumentation, and evidence. I think we will find we have a lot to say to one another.

A second domain is that of literacy and identity issues: how do students perform their various affinity 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, who they imagine they could become? This is a very crucial issue for science educators because the stereotypical self-presentation of science is so often at odds with the kinds of identities students, esp. adolescents, want to perform.

Finally, there is a large 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. Wechsler 1977, Tauber 1996). Too often science presents itself only in terms of the results of research and does not say much about the process itself, and when it does there is an over-emphasis 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 ones for which connections to adolescent identity can potentially be made. Research on identity and adolescent engagement with literature and in their own writing should provide helpful guidance to a science education that is serious about the humanistic side of real scientific work.

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