Teaching All the Languages of Science: Words, Symbols, Images, and Actions

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Languages and Concepts in Science

If you ask most teachers of science what their main goal is, they will probably say: for my students to understand the basic concepts of physics, chemistry, biology, or whatever other field is being studied. The critical words here are "understand" and "concept", and both of these terms assume a fundamentally _psychological_ approach to learning. They belong to the tradition of _mentalism_, in which concepts are mental objects and understanding is a mental process. In more modern terms, they belong to a _cognitive_ model of science education. I do not believe that this kind of theoretical model can tell us enough to help us to become better teachers of science. I believe that it lacks the necessary vocabulary to tell us just what we must lead students to _do_ in order to learn to reason and act scientifically.

It was my dissatisfaction with the traditional mentalist view of education that led me in the late 1970s to explore other theoretical traditions. There have always been other kinds of answers to the basic question of our goal in the teaching of science. We can also say that we wish students to reason in the ways that scientists reason, that we wish them to be able to use the tools and practices that scientists use as part of their activities of problem-solving, discussing scientific issues, and participating in everyday life in a technological society. We can make the goal of science education learning and using particular ways of making meaning about natural and technological phenomena, we can make it be engaging meaningfully in the kinds of patterns of action that scientists use in their work.

These alternatives do not contradict psychology, but they are more consistent with some psychological theories than with others. In particular, they are more consistent with theories of social psychology and social developmental psychology, such as those associated with the names of Lev Vygotsky (1934, 1978) or, in his later work, Jerome Bruner (1986, 1990), than they are with mainstream American cognitive psychology of the 1970s and 1980s. If we see the goals of science education in terms of what students will be able to do, and how they will be able to make sense of the world, rather than in terms of our speculations about what may be going on in their brains, then we need to see scientific learning as the acquisition of cultural tools and practices, as learning to participate in very specific and often specialized forms of human activity.

This alternative view places more emphasis on the role of the teacher as someone who can model for students how scientists talk and write and diagram and calculate, how scientists plan and observe and record, how we represent and analyze data, how we formulate hypotheses and conclusions, how we connect theories, models, and data, how we relate our work and results to those of other researchers.

Traditional cognitive psychology is not a theory for teachers, nor a theory of education. It is an attempt to build a universal model of all human thought. It is founded on the assumption that the ways in which all build a universal model of all human thought. It is founded on the assumption that the ways in which all thought is alike are more important than they ways in which we all think differently in each specific activity of life, think differently in each particular concrete situation in which we find ourselves. A critic might well say that existing models of universal thought are mainly premature over-generalizations from observations of just a few kinds of thought (mainly logical-mathematical and some simple and idealized physical problem-solving), by just a narrow range of people (mostly American university undergraduates and a few technically trained experts), and in very artificial situations (the psychologists' carefully controlled laboratory settings).

There are today many alternative views, from those which point out the implausibility of the view that thoughts can directly represent realities or actions (e.g. Bickhard 1995), to those that emphasize the situatedness and specificity of different kinds of reasoning in different concrete conditions and challenge the assumption that the general basis of human thought is abstraction. Both Situated Cognition Theory (e.g. Lave 1988, Rogoff 1990, Saxe 1991) and the neo-Vygotskyan Activity Theory models (e.g. Leontiev 1978, Engestrom 1987, Wertsch 1991), as well as general Cultural Psychology (Cole 1996, Cole et al. 1997) recognize that thinking is a kind of material action, and that it is conducted not just in and by the human brain, but by the whole body, making constant use of material tools and artifacts in the environment, and interpreting its own actions and their results by means of socially learned and culturally specific systems of meaningful signs, such as the languages of words, diagrams, and mathematical symbols. Year by year more new research defines itself as socio-cognitive or socio-cultural in these terms, rather than as a purely mentalistic psychology.

Teachers of science should rejoice that at last researchers are looking beyond their pet theories about the human mind and actually studying what teachers and students say and do in the classroom, in the laboratory, and wherever science is being learned and practiced. Looking at meaningful action and activity, at language in use, at all forms of verbal and non-verbal communication in real classrooms, laboratories, museums, and virtual on-line environments (e.g. Lemke 1990, Roth 1995, Cobb et al 1993; Newman et al. 1989, Michaels & O'Connor 1993; Kamen et al. 1997).

This change in our view of learning science, from just a mentalist psychology to the comprehensive study of all the meaningful ways that people engage in specifically scientific forms of human activity is paralleled by great changes in our view of what science itself is and how it is practiced. For a very long time scientists and the philosophers who built their reputations on the prestige of science have had their own way in providing rather self-serving views about what science is and how it is practiced. Most working scientists have never taken these view very seriously, and neither have they felt it worth the effort to contradict them. In the last few decades, however, sociologists trained in both science and social science methodology have begun to carefully observe and analyze what actually happens in scientific laboratories, discussions, conferences, and journals (e.g. Latour 1987; Lynch & Woolgar 1988; Ochs 1996) Their picture is very different from the traditional one.

Science is not a pure form of rationality; it is not an ideally objective pursuit of truth, guided by the dictates of nature alone. It is a very human activity, full of biases and accidents, driven by egos and budgets, competitive and sometimes venal, tightly locked into the agendas of larger institutions and social movements: a wonderful and terrible human comedy, like every other part of life. Science cannot be equated with its products: what science says about the world is not science itself. Science itself is the human activity that produces these statements and theories, and to learn science is not to learn what the last generation of scientists thought the world was like: it is to learn how each new generation of scientists re-makes our view of the world. Ultimately, it is to learn how to have some degree of participation in this process of invention and discovery.

But mentalist psychology does not have much to say about science as a social activity, as a system of interdependent actions and practices that produce scientific statements and theories. It does not tell us how and why a scientist undertakes her next experimental project, or how she connects the results of an experiment to other experiments and existing and new theoretical models. It does not tell us how scientific views are constructed during dialogue and the exchange of ideas, or influenced by cultural value systems and disciplinary traditions. It has little to say to us about how to model the practices and activities of science for our students, how to help them learn to integrate these various practices into some semblance of the ways that scientists act, or how to learn to be even peripheral participants in the world-spanning activities of scientific communities.

What sorts of theories _are_ useful in this respect? I have already pointed to social and cultural psychology and to the sociology and ethnography of science, but these models also fall short for our purposes as science educators, because we are not their primary audience, our purposes are not their purposes. Even within these emerging alternative theories, there is also recognition that some tools and some perspectives are missing, that the logical and explanatory chain from overall activity to moment-to-moment action cannot be completed unless we look at how people actually deploy resources for making meaning, actually engage selectively in meaningful actions, as part of larger agendas and activities, and this means that we need to look at one more theoretical picture of science education.

I have called this additional perspective that of "social semiotics" (Lemke 1990, 1995). Back in the late 1970s and early 1980s when I did the research that was eventually published as _Talking Science_ in English (and in Spanish as _Aprender a hablar cienca_, 1997a), I knew that the results of audio- and video-recording and close observation in science classrooms produced massive amounts of transcriptions of what words were said, in what contexts, what diagrams were drawn on the chalkboard and in students' notebooks, what equations were written, what graphs interpreted, what demonstrations performed. I knew that the progress of learning in these classrooms was manifestly a function of these small details, that it was the dynamic development of a trajectory of meaningful action, socially shared and jointly constructed by teacher and students, that produced learning. I think that every teacher knows this; we all seek to make meaning jointly with our students, to become engaged together in scientific sense-making, scientific doing.

If this is the heart of teaching, this progressive sequence of things we say, diagrams we draw, equations we write, experiments we perform: how can we analyze the nature and extent, and difference, of our participation as teachers in this meaning-making vs. the participation of our students? Here is where I locate the contribution of social semiotics, which addresses just these questions.

Semiotics, most basically, is the study of how we make meaning using the cultural resources of systems of words, images, symbols, and actions. It looks at every object and action as a sign, as having a meaning that goes beyond its properties as a material object or process, a meaning _for_ some other system, which interprets the sign as having this further meaning (e.g. Peirce 1955 and Houser & Klossel 1992; Saussure 1915). _Social semiotics_ looks at these meaning-making practices and activities as social processes, as something we learn to do as members of communities, and which we tend to do in characteristic ways that index our communities as much or more than our own individuality.

Language itself is the most pervasive system of semiotic resources, and the ways in which scientists use specialized languages and use common language in specialized ways index the discourses of the communities of scientific disciplines. Every word is rich with meanings, meanings that accumulate as we encounter it in many different contexts. Every word is an intersection of many statements, many discourses that make use of it. Every word-in-context is part of some possible exchange of meaning between different members of a community (cf. Lemke 1998b). And what is true in this way of words, is no less true of pictures and diagrams, graphs and maps, equations and symbolic representations, and the symbolism of actions that mean as well as cause.

In the early stages of my work, I focussed only on language. I did so not because I did not recognize the importance of the visual, mathematical, and actional-operational "languages" of science, but because at that time the needed tools of analysis existed for language (e.g. Halliday 1985/1994, Halliday & Hasan 1976), but not for the others. When I used the term "languages of science" in the 1980s, I usually meant the specialized languages of physics, of chemistry, of biology and the other scientific disciplines and their communities. I meant what today would be called the linguistic registers and genres of these fields: their vocabularies, their semantic networks, their styles of discourse, their standardized types of documents, etc.

Today, however, I want to put before you the case for using this phrase, "the languages of science" in a broader sense. I want us to recognize that in addition to scientific English, or Spanish, or Catalan, there are also other essential "languages", in the sense of cultural systems of semiotic resources in science: the languages of visual representation, the languages of mathematical symbolism, and the languages of experimental operations. The goal of science education, I want to argue, ought to be to empower students to use all of these languages in meaningful and appropriate ways, and, above all, to be able to functionally integrate them in the conduct of scientific activity.

How Science Says What it Means

A few years ago I decided to have a close look at how scientists "say" what we mean (Lemke 1998a). I looked at our proudest products, scientific research articles for publication. I examined the most prestigious of the general English-language scientific journals, _Science_ published by the American Association for the Advancement of Science, and its British counterpart, _Nature_. I also looked at some physics journals and across a range of advanced textbooks and treatises, to see the whole range of science, from molecular biology to field ecology, from particle physics to cosmology. What I saw on the pages of these books and journals was never words alone. On every page there were also visual-graphical representations of many kinds, as well as mathematical equations, and charts and tables.

For example, in the prestigious _Physical Review Letters_, there were an average of at least one and often two or three graphical figures (tables, charts, graphs, photographs, drawings, maps, and more specialized visual presentations) per page, as well as at least 2-3 and often as many as 6-7 equations per page. In _Science_, with more experimental and few theoretical articles, there were fewer equations, but on average one table, one data graph, and a total of 4-5 visual graphics of one kind or another per article. In the broader survey as well, there was usually at least one graphic per page and, if equations were used, 1-2 of these per page as well.

Some extreme examples help to make the point:

= In one advanced treatise, a diagram was included in a _footnote_ printed at the bottom of the page (Berge et al. 1984: 84). It was necessary for even the minor point being made there. = In one 7-page

(Berge et al. 1984: 84). It was necessary for even the minor point being made there. = In one 7-page research report in _Nature_, 90% of a page (all but 5 lines of main text at the top) was taken up by a complex diagram (Svoboda et al. 1993) and its extensive figure caption. = The main experimental results of a 2.5-page report in _Nature_ were presented in a set of graphs occupying one-half page and a table occupying three-fourths of another (Martikainen et al. 1993). 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 as if part of the verbal text. Science does not speak of the world in the language of words alone, and in many cases it simply _cannot_ do so. The natural language of science is a synergistic integration of words, diagrams, pictures, graphs, maps, equations, tables, charts, and other forms of visual and mathematical expression.

Why should this be so? I will return in more detail to this question later, but for now consider how poor language is in resources to describe continuous variation and complex matters of quantitative relationship. How well could you describe in words the shape of an irregular surface, twisting and bending in 3-dimensions? How well could you describe the exact quantitative relationships between two curves on a Cartesian graph? or even give more than the most rudimentary view of their changing differences in qualitative terms? What non-mathematical resources do we have in natural language to describe complex ratios and rates of change of rates of change? or general functional relationships more complex than those of simple linear proportionality? Natural language is very limited in its ability to describe continuous variation, shape, and movement in space. Gesture is a more suitable language in which to express such meanings. And drawings and visual depictions, which are in many ways the lasting traces of gestures, standing to gestures as writing does to speech, are the time-independent medium of choice for such expressions of meaning. For quantitative relationships, we have furthermore extended natural language with the language of mathematics, and learned to use mathematics as a bridge between verbal language and the meanings we make in visual representations.

Concepts as Multimedia Signs in Use

So, have we then totally lost the notion of a scientific concept and its understanding? How can we translate these traditional terms and the many useful understandings of our work as science educators that we have formulated with their help into the new and broader theoretical language of the social semiotics of scientific activity?

In the traditional mentalist view, a concept exists outside of all language, and indeed outside of all languages, in the sense of representational systems like images, symbols, actions, etc. It exists in some imaginary "lingua mentis" -- the very metaphor relies on the notion of a language, of a semiotic resource, a "language of the mind". This is only a fairly recent effort to make plausible a very old idea: that a concept as an abstraction exists in a realm of its own, beyond the material world. We heard this first from Plato, and there is for me little distance between the mentalism of Descartes and the idealism of the Platonists. The most popular view today among philosophers is of course radically anti-idealist; it calls itself Realism, and in its most comprehensible form it simply says that there is some correspondence between the ideas of the mind, our concepts, and the realities of the objective world. The concept of energy exists in the mind, but it has some correspondence to a real phenomonenon of energy in the material world. It is the reality of the phenomenon which gives a unity to the concept, and allows it to exist above and independently of all possible representations of it. Frankly, I find this view distressingly theological; in fact its intellectual possible representations of it. Frankly, I find this view distressingly theological; in fact its intellectual distance from the idea that the soul exists in a realm separate from that of the material body does not seem very great.

All these imaginary mental realms are also pretty much unnecessary for making sense of human activity. Yes, we certainly need something more than crass materialism; we need more than a universe in which there are only material causes and effects. But we do not need a second non-material universe, whether of souls or minds, we need only a second interpretation of the one, single material universe. We need only to add meaning to matter, interpretation to causal effect, so that every material object and process can also function for us as a sign, as something that means more than it does. And how do things mean as signs? this is one of the basic questions for which semiotics supplies useful answers.

I cannot summarize all of semiotics in a few words, but for the purposes of my argument here, let us just say that as a sign an object or process means because we connect it, in a relation of similarity or difference, of kind or degree, to some set of alternatives: this word vs. that word, this image vs. that image, this action vs. that action. More importantly, signs do not occur in isolation. They are produced and deployed in clusters or arrays, whether as sentences or images or mathematical proofs and derivations, and these arrays mean as wholes as well as meaning through each part and sub-unit, and each of these different scales of meaning also operates by difference and degree, but more interestingly by their typical and expectable (or surprising) relations to various contexts. The symbol "V" may denote velocity in one context, and voltage in another; how do we know which? because of some pattern in the array (a legend, an accompanying text) that we have learned to connect with the symbol (as a standard genre), or because of some typical and expectable connection to the situation, to the larger activity in which the array occurs (is this a lesson on electricity, or it is a lesson on kinematics? are we seeing a demonstration of motion, or one about electric circuits?).

What, then, in semiotic terms, is a scientific concept? is it the word "energy" and the ways we use that word? is it the symbol E and the mathematical equations in which that symbol appears? is it a diagram of energy levels, or a graph of potential energy wells? is it the set of procedures for experimentally measuring thermal or electrical energy in some system?

In the mentalist-realist view, each of these is just a shadow of the Idea of Energy, a reality in the world and a concept in the mind; each of these representations of Energy can be made equivalent to the others because of the reality of Energy as an actual and existing phenomenon.

In the semiotic view, there is no real phenomenon corresponding to the concept of energy; rather, there are only a great many complex material phenomena which can be interpreted or construed according to various discourses and symbolic schemes, one of which uses a notion of energy. What makes all the different semiotic representations for "energy" equivalent to one another is not the reality of "energy" but the work that we learn to do to construct these equivalences one by one, pair by pair. This work is the product of a long historical tradition telling us how to use these various symbolic representations effectively.

These two views have profoundly different implications for the teaching of scientific concepts. On the mentalist view, students should be able to "discover" the concept of energy for themselves; they should be able to "generalize" from different instances of energy and "see" the conceptual unity of the various representations of energy. It should be possible for them to "leap" to the abstraction because in some sense that abstraction is real, and is always naturally there as a target for their leap.

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In the semiotic view, the "discovery" scenario is a dangerous and misleading fable. Students need to be taught, in each separate kind of physical instance of "energy", how to measure "energy" differently, how to use the word "energy" to refer to specifically different aspects of a system or phenomenon, how to write equations that apply to that type of system, how to draw diagrams for it; and then they need to be taught how to move back and forth among the different verbal, mathematical, visual, and operational representations for "energy" in each case, and then further how to integrate and construct equivalences between each different pair of types of cases. They need to gradually build up an abstract concept of energy, for there is nothing there to "leap" to until they have learned how to construct the necessary equivalences.

Yes, of course, a very few students do seem to leap to some concepts. I think we know that these are students who already have quite a few more clues about how such integrations and equivalences are supposed to be formed than do the other students. One should not under-estimate the ability of the human brain to identify patterns, including those which are the historical product of various forms of reasoning in our culture. What we call the very bright students are usually those whose lives outside school are rich in examples of abstract patterns of reasoning inherited from the same elite cultural tradition that gave rise to our scientific concepts. But even these students do not make too many lucky guesses, and most of them will also have already read a fair bit about the subject beforehand.

Those who are well-versed in the history of science will more easily understand the semiotic position. I chose the concept of energy deliberately because it falls about mid-way in the range from scientific concepts that seem totally natural, such as "mass" or "heat", to those that seem totally artificial, such as "entropy" or "action" (the quantity of which Planck's constant is the minimal unit). "Energy" has been naturalized by history, but there was a time when it seemed as arbitrary and artificial, as purely a mathematical convenience unrelated to material reality, as such older notions as the "vis viva" or "impulse" or current ones such as "Gibb's free energy" or "enthalpy". Historically, each new "form of energy", from heat energy, to electrical and magnetic energy, to nuclear energy had to be defined and constructed in completely different terms; there was no Idea of Energy to point us in the right direction, there were only the accepted experimental processes for establishing equivalences of quantity, and in fact in many cases these themselves had to be invented, and we give great scientific recognition to Joule and Kelvin and Faraday and Maxwell and all those others who first showed the ways to fit new cases into an expanded paradigm of energy. In semiotic terms the concept of energy changed and expanded as each new kind of energy was integrated into the grand synthesis of physics.

Neither of course does the concept of energy have sufficient reality in its own terms to insure that it will continue to be applicable in all possible physical situations, as it is not in cases where the uncertainty principle forbids a system to be in an energy eigenstate, or where space-time is so radically convoluted in its topology that "energy" can no longer be usefully defined as the time-like component of the momentum 4-vector or one cell in a 10-component 4-dimensional stress matrix that only exists in a co-ordinate frame that cannot be defined too close to a black hole singularity.

No scientific concept re-presents a pre-existing absolute reality; every scientific concept offers a means of interpretation of our experience in the world, including the world of the laboratory, and the worlds we model for cosmological phenomena and conditions. Every scientific concept is an element in a system of signs, and indeed is a conflation or integration of simultaneous and conjoined elements in several very different systems of signs. This fact is, I believe, critical for our work as science educators.

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Every scientific concept is simultaneously a sign in a verbal semantics of discourse, and in an operational system of actional meanings, and usually also in a visual representational system, and frequently in a mathematical semiotic system as well. And its meaning does not arise simply from each of these added to, or in parallel with, the others: it arises from the combination of each of these integrated with and multiplied by each of the others. From this multiplication of meaning comes the great power of scientific concepts and of scientific reasoning: in scientific reasoning we can freely and self-consistently move back and forth between verbal reasoning, visual reasoning, quantitative reasoning, mathematical symbolic logic, and operational situated sense-making.

We can integrate all of these modes to solve problems that could never be solved with only one or even two of them. We can partly talk our way through a scientific event or problem in purely verbal-conceptual terms, and we can partly make sense of what is happening by combining our discourse with the drawing and interpretation of visual diagrams and graphs and other representations, and we can integrate both of these with mathematical formulas and algebraic derivations as well as quantitative calculations, and finally we can integrate all of these with actual experimental procedures and operations, in terms of which, on site and in the doing of the experiment, we can make sense directly through action and observation, later interpreted and represented in words, images, and formulas.

But it is precisely how to accomplish this miraculous synthesis of multimedia reasoning which most of our students do not learn to do. And this should not be surprising to us, because in general our curricula include almost no explicit instruction or practice in how to do it. We leave it all up to the students to work out for themselves, because we have been terribly misled by mentalist psychological theories that tell us that a "bright" student ought to be able to "think abstractly" and so re-create in a few weeks what our scientific history took decades and centuries to construct. Those who cannot do so are labeled hopeless, and the powers that be in society smile to discover that more sons of the well-to-do classes make successful guesses than do the sons of the poor, or anyone's daughters.

Teachers do not smile when any student fails. Teachers want to be able to understand what it is that students are not learning how to do. We want to know what the missing links are that are needed to connect what we teach them with what we expect them to be able to do. As teachers we all want to know: what is it that we should have taught them to do, but didn't?

Lessons from A Case Study: John Juggles Multimedia Science

Recently, I was asked to analyze a video-tape of one day in the life of a student in an Australian high school (Lemke 1997b). In the last year of advanced work in science, this student, John, was taking, in one day, a chemistry and a physics class, with lunch and some mathematics in between. What was unusual about the videotape was that it showed the student's view of the classroom; the camera was located next to and a little behind the student, at the end of one row of seats, and it showed his activity and his view out over the rest of the classroom. The point of this research study was to look through the student's eyes, to take the student's role perspective on classroom interaction and learning. In addition to the videotape, I had access to the relevant pages of the textbooks, to the teachers' overheads, handouts and notes, and to the student's own notes from his notebook.

So I began this analysis, and in particular I focussed on what different media and channels of information were conveying scientific information to John, and what media and tools John was using to interpret this were conveying scientific information to John, and what media and tools John was using to interpret this information. I could not see John using concepts as such, but I could see him reading from a textbook, writing in his notebook, looking at a diagram on the chalkboard, using a calculator, talking to a friend in the next seat, listening to the teacher and other classmates ... and even I was astonished at how many different semiotic systems John had to integrate and make use of in every few minutes of time in the classroom. John was becoming an expert at juggling the many media that together make up scientific activity. Of course John was successful in science, or he would not have advanced to these classes. He was one of the lucky ones who was correctly guessing by trial and error what he had to do to make sense of what he was being taught.

Indeed, we should be very careful when we speak of "what is being taught", for there are things being said, and diagrams and graphs being drawn, and written material distributed, and demonstrations performed ... but this tells us nothing about how John _interprets_ these signs. Given the large number of students who either fail at science, or who pass but really cannot use what they have learned, and the many who choose not to take courses in science, we can assume that most students are not like John; for most of them most of what we say and write and draw and compute and demonstrate makes very little sense, or at least not at all the kind of sense that is needed to succeed in science.

We teach _in_ the languages of science, but we do not very often teach students _about_ those languages. It is as if we taught our English or Spanish or Catalan students in Chinese; as if we drew all our diagrams in secret codes, and represented all our formulas in encrypted form, as if the meanings of our actions were arcane and esoteric rituals. From our point of view we are presenting the content of science in as plain and clear a manner as possible, but this is useless if the students cannot decipher the languages in which we are saying and showing it. In fact, the situation is perhaps even worse than this, because to arrive at the meanings John needs, he must not only make sense of each of these languages separately, but he must understand the special ways in which the teacher combines and integrates them with each other. Time and time again in my analysis of John's lessons, it was clear that the teacher was not presenting the whole idea in any one language: it was only by combining a partial meaning from the words, with a partial meaning from the diagrams, and another partial meaning from the mathematics or the demonstration that a whole, sensible meaning could be formed. It is as if we taught science plainly and clearly, but we said the first words of each sentence in Chinese, then the next few in Swahili, and then the last few in Hindi, and in the next sentence we started in Swahili, ... and so on.

Of course the languages of science in which we teach are not totally alien to our students, but much in each of them is quite new, and the ways in which they must be combined to make complete meanings are totally unfamiliar to most students, especially in the first year or two of serious and intensive study in science.

Not only are the meanings which teachers make in each separate channel of communication often incomplete in themselves and insufficient by themselves as a basis for inferring the correct scientific meaning, but frequently what teachers communicate in one channel is simply wrong, or misleading, if taken out of the context of what we are communicating in the other channels. Teaching is a fast-paced activity, as every teacher who races the clock to finish a lesson knows. As humans, we teachers are fallible, and we often mis-speak, and mis-write; we say things reversed, we mix-up two numbers or symbols, we leave something important out, we say just the opposite of what we mean to say, we write something in the wrong column, we skip a step in a derivation, we use the wrong symbol ... and it is truly remarkable that many of our students simply note our mis-steps, see them as obvious errors, correct them based on other things we've said, or what is on the sheet or in the book, or on the chalkboard, and only occasionally get confused enough to have to ask us if we made a mistake. These tiny lapses are really rather common if you examine transcripts and videotapes; mostly they are erased in memory by the next thing we say or write or draw or do, which sets all to rights. Human communication is a fault-tolerant system, it incorporates a great deal of redundancy, especially if we average meaning over longer stretches of time. But in order for these self-correction mechanisms to work in science teaching, students again must be able to integrate the meanings that are communicated in different channels, using different semiotic systems of resources for communication.

Another feature of the multimedia communication of science is what is called fashionably today its _intertextuality_. This is a principle, in linguistics and literary theory, which says that we make sense of each item we read or hear or see partly by comparing it with other things we have read, heard, or seen somewhere else. One writer makes literary allusions to another book or novelist; a painting is meant to trigger our memory of some other classic work of art. And in simpler ways, what the teacher says right now may make sense only if the student remembers something read last night in the textbook, and what is read there may make sense only in the context of what was written in the previous chapter, and the diagram on the board may make sense only when we have also heard the verbal discussion of it, and the relationship in a formula may become meaningful to us only when we have entered some sample numbers on our calculator to try it out. Some students make sense of the graph before the formula, others the verbal statement before the mathematics, some may make sense of the demo only when they have also seen the diagram, and so on. Sometimes all the necessary information is present simultaneously in the classroom; more often it is presented to us only serially one bit after another, maybe in the best order for us individually, and may not. Patience is required, and trust that the missing pieces of the puzzle will be shown later. Many times not all the needed information is present today, we must remember from yesterday or last week or last year, or we must remember what we read in the textbook, or the problem we did as homework. And sometimes we need a little piece of the puzzle that is nowhere to be found in the school curriculum, but that we experienced in the science museum we went to with our family. If we are lucky enough to be born into the kind of family that goes to science museums.

These puzzle problems, this juggling of different information sources, is not some weakness of a poorly prepared teacher. It is inherent in two aspects of all communication: that no meaning is ever complete in itself (there is always a necessary intertextuality), and that every interpreter finds a different pathway to meaning (sometimes an amazingly bizarre and idiosyncratic one). Science above all disciplines, except possible mathematics, prides itself on its explicitness and completeness, but these are ideals that can never be totally achieved. A completely explicit text would be an infinite text, and indeed no text in a single medium can ever stand on its own ... all depend on co-reference to other aspects of meaning and experience. All communication must make some assumptions about what the reader will already know as a basis for further interpretation. And likewise, what every actual individual reader does know is different, and no two readers will interpret any text in exactly the same way, especially if it is a long and complex one. Perhaps they may even come to the same conclusions, but by very different pathways. And many times they will not even come to the same conclusion.

This is one reason why teaching is a dialogue. It is only by on-going interaction that teacher and students have the chance to compare their interpretations of what each other is saying, and so gradually come closer to functionally equivalent meanings -- to interpretations that may still differ, but do not differ in ways that will cause the cooperative progress of the dialogue or the experiment to fail. Every teacher believes that he or she is capable of making a perfectly clear explanation that will be understood by every student. And every teacher knows that in this belief we are quite wrong. It is not a matter of our brilliance or clarity; it is simply not a human possibility.

In every typical few minutes of his work in these science classes, John was listening to the teacher's spoken words, but also looking at diagrams and lists and tables and calculations and equations written both on the chalkboard and displayed on an overhead projector screen. He was listening to his classmate's answers to the teacher's questions, and to her evaluations of those answers (for only the three together make a complete meaning). He was consulting a copy of the textbook and relating what he found there to statements, to questions and answers, to the tables on the board and screen. As he followed the explanation of a method of problem-solving, he was getting ahead of the teacher by using his own calculator, and then comparing his result with hers. He was writing in his notebook, sometimes copying from board or screen, sometimes copying from textbook, sometimes transcribing teacher talk, sometimes formulating his own version of a conclusion of a question-answer-evaluation discussion. His notes integrate all these sources into a reasonably coherent exposition, and they too contain not just the words, but also the tables, the diagrams, the equations and calculations -- John's versions of these, not identical to the teacher's, sometimes more correct than hers, sometimes less.

In the physics class there were also demonstrations of emission spectra and laser light, and the teacher did a visual pantomime of coherent emission and amplification in an imaginary laser crystal, all invisible, but clearly followed by most of the students as they visualized the crystal and the photons from his verbal narration, his gestures, his movements through the (large) imaginary crystal. They relied on memory of other diagrams and pictures that they had seen in the textbook and perhaps in another lesson. And they drew in their notebooks real drawings of invisible, imagined objects created solely by the narration and pantomime of the teacher and never drawn at all. This is visual intertextuality, it is visual-verbal integration, it transforms gestures into drawings through the joint work of teachers and students, mediated by verbal language cues, both more and less successfully.

John and his classmates were constantly integrating, translating, comparing, and synthesizing information presented in verbal form as complete sentences but more often as incomplete phrases, as lists, as mathematics spoken aloud, as propositions spread out over question, answer, and evaluation of answer; together with visual information from written text, from graphs and diagrams and tables and charts; and information conveyed in the language of action and procedure and demonstrated operation, as well as in the language of mathematical symbolism and numerical calculation. I emphasize that complete ideas and relationships were _not_ presented separately in each of these channels; they were not redundant. Complete meanings usually could be made in each few moments only by integrating information from several channels. This is a normal feature of human, and especially of scientific communication. We find it in professional scientific discussions (e.g. Ochs 1996) and in published scientific research articles (Lemke 1998a) just as much or more than we do in these classrooms.

John did all this juggling and integrating fairly fluently, though we do not know how well he would be able to marshall these skills and multimedia concepts to do original work in science. John was a mostly silent participant; we can judge him mainly by what he wrote in his notebook and his judgment in consulting the relevant sources at the relevant moments, his ability to correct a few errors the teacher made, his ability to use his calculator to get a few steps ahead of the teacher at one point.

John is one of the lucky ones. He is an advanced science student who has learned to juggle and integrate and synthesize across the multiple semiotic languages of science. He made a lot of correct guesses earlier in his learning in science, and/or he had some special help and guidance, or some strong motivation and discipline to work through many wrong possibilities until he found ones that worked. Too many students are not as lucky as John. Too few curricula and standard teaching methods in science place enough emphasis on teaching students how to do what John has learned to do. It is our responsibility as teachers to develop the methods needed to teach all students how to talk the specialized verbal language of science, to create and interpret the specialized visual representations of science, to use the mathematical and quantitative symbolisms of science, and to execute and interpret the language of practical actions and operations that tie meanings to doings in science. More than this, it is also our responsibility to teach students how to explicitly integrate these different modes of representation, how to shuttle back and forth among them, how to reason with them in complex combinations, how to communicate their ideas and results through syntheses among them.

Why Does Science Use Multiple Semiotics?

I assume that science educators are intellectuals as well as practical men and women. For very practical reasons, we all need to know more about how science and the teaching of science relies on the integration of multiple channels of communication and the use of multiple systems of semiotic resources. We need to know these things practically because these are the very media we use in our own teaching, they are the tools of our trade, and we must learn to use them and teach our students to use them as well as we can.

But as intellectuals we should also have a more basic curiosity: why is science like this? why does science need to use multiple semiotic systems? why would just verbal language alone not be enough? why would mathematics alone not be sufficient? could we teach students all they need to know using only verbal language and visual diagrams and graphs? in what sense is it really true that experimental procedures themselves form a communication system very much like language itself in the way that it works?

I cannot hope to give satisfying answers here to these profound questions, but I think it is worth considering at least a few bits and pieces, a few hints, toward possible answers.

We might begin with one of the oldest questions of science: why has mathematics proven itself so useful as to be indispensable in the work of the natural sciences? This was of course the basic concern of the Pythagoreans in ancient times, who found it profoundly mysterious, and indeed a matter of religious inspiration, that mathematics could be formulated as a purely logical system, apparently independent of our experience of the world, and yet seemed to so perfectly suited to describing its forms and processes. Plato's idealism was of course itself inspired by more or less this same observation. But the Greeks, and especially the philosophically minded ones, however large they are made to loom in our historical myths, were in fact rather minor players in the ancient world, and most of them abhorred philosophy. Greek mathematics came mostly from Egypt and perhaps from Crete, and these systems of mathematics seem to have come mainly from the ancient Babylonians, who were remarkably advanced. They solved complex algebraic equations, had trigonometric tables and rudimentary logarithms, and they had the beginnings of integral calculus (Neugebauer & Sachs, 1945; van der Waerden 1963; Joseph 1991) Their mathematics was entirely practical and driven by practical problem-solving concerns. So, by and large was that of the Egyptians (Peet 1923, Neugebauer 1975, Cajori 1928). With rare exceptions, most of the history of mathematical development is the history of inventing mathematical techniques and concepts to handle practical problems _that could not be handled adequately by verbal reasoning alone_.

The origins of our mathematical tradition lie in the tools devised by engineers and surveyors, agricultural superintendants and tax collectors. The collections of problems in Babylonian and Egyptian mathematical texts were almost always illustrated by diagrams or verbal descriptions of geometrical, figural relationships. The great first steps of these mathematical systems, from which our own derives by way of the Greeks and then the Arabs, were to find ways to represent symbolically, and operate symbolically with non-simple ratios and algebraic equivalents of geometrical relationships: they were in a profound sense creating a mathematical language for the description of quantitative relationships more complex and precise than natural language before that time was accustomed to handling.

The history of mathematics is a long and complex one, but until relatively recent times, most of its progress was driven by very practical problems of representing material relationships and processes, first as matters of complex ratios or rational numbers, and later as decimal numbers in the continuum of the real numbers. When human beings came to reason about lengths and areas, about angles and rates of change, about motion and shape, we found that the semantics of natural language was not well adapted to such tasks. Natural language operates primarily by contrasts between mutually exclusive categories (human vs. animal, singular vs. plural, move vs. stand) and it has relatively fewer and limited resources to express quantitative meanings or meaning-by-degree. There are the counting numeratives (integers), the simple multipliers (twice, thrice), and a few degrees of comparison (big, bigger, very big). Indo-European languages also distinguish mass and count nouns ("five lakes" but not "five waters") and introduce quantifier terms that become the basis of our notion of units of measure (five pails of water, five bushels of grain). There were also a few simple fractions (one-half, two-thirds) but the possibility of creating multiples (seven one-twelfths, or thrice a sixth) already represented an extension of natural language into an unfamiliar domain.

Natural language gives us no clue as to which is larger: seven elevenths or eight twelfths? but a geometric representation would be quite clear on this point. In general the resources of visual representation were better able to handle matters of proportion and ratio, and complex shape, pathway, or direction of motion, than natural language. In time, visual representations came to be indispensable codings of material relationships in order to reason about them, but reasoning remained still a kind of use of natural language. All our categories and logical operations were embedded in natural language, and not until very late in semiotic history do we find visual logics of equal power. Most of our questions and problems to be solved were posed in language and expected answers in language. The early mathematical texts are mostly in verbal prose, with diagrams added, and only a little specialized notation, mostly for large numbers and odd ratios. What was desperately needed in order to reason about the material world was some way to connect the categorial logic of natural language with the quantitative and geometrical descriptive power of visual and numerical signs.

This connection of course was made, in many small steps, by the invention of algebraic notations. In the ancient texts, and even well into the Renaissance, algebraic notation was always embedded in natural language and written simply as an extension of prose verbiage (Cajori 1928). Our modern efforts to suppress natural language and operate purely in mathematical symbolism are quite foreign to most of the history of mathematical and scientific reasoning. Algebra was fundamentally an extension of the semantics of natural verbal language to allow it to express and reason about complex ratios of quantities, and arbitrary geometrical shapes and spatial motions and temporal changes. It was at first a supplement to both verbal language and visual diagrams, and finally with the appearance of co-ordinate geometry (anticipated in most of its features long before Descartes), there was a complete bridge, a constructed equivalence between the mathematical formula, the visual graph, and the quantitative variation observed in measurement operations. This unification more or less coincides with the birth of modern science, and made it possible.

All semiotic resources, whether verbal language, mathematics, or visual representation combine two basic principles for making meaning: meaning by kind and meaning by degree (see Lemke 1998a, In press, and In preparation). The first, or typological semiotics, is more familiar to students of linguistics and sign systems analyzed by analogy to natural language. All meanings are about category terms and relations among them, even categories of processes and categories of relations. Most categories are mutually exclusive, and membership in a category is all or none. The second, less familiar but extremely important for science and science education, we may call a "topological semiotics" (see references above). Here, as in the languages of visual representation and human movement, posture, gesture, and proxemics, the meaning of an element can change by infinitesimal degrees, instead of simply switching from one category to another: shades of a color, relative proximity in space, lengths of a line, curvature of a shape, rate of motion. Of course natural language has some capacity for meaning by degree, as in evaluations and judgments, or more clearly in matters of audible speech such as intonation and forcefulness, but this is not its forte. And so likewise visual representations certainly also rely on contrasting categories, as in the representation of familiar types of objects. But drawing and gesture are much more powerful at expressing topological, and therefore quantitative meanings, while verbal language is much better at reasoning about relations among categories.

The phenomena of scientific investigation possess critical features of both kinds: to characterize material processes and their relationships we need both categorial descriptions and quantitative reasoning, and this fact created a historical pressure that gradually built a bridge between the linguistic and the visual-gestural: the result was mathematics, built out from the linguistic as the algebraic extension of the semantics of natural language in matters of quantity, ratio, and continuous variation, and built out from the visual-gestural side as geometric diagram and eventually Cartesian graph. The ability in mathematics first to create correspondences between algebraic and geometric representations, and eventually to construct complete equivalences between them provided the missing link that enabled science to reason both verbally and quantitatively, both typologically and topologically, about material phenomena and processes.

And this is why, I believe, modern scientific concepts are essentially elements in the cross-articulated multiple sign system of language-mathematics-visual representation, with a final link to the actual operations of experimental manipulation of apparatus and measurement. It is easy enough to see that there must be a link between semiotic representations and reasoning and the phenomena themselves, and also easy I think to see that this link must come by way of the actions of the scientist in interacting directly with the phenomena under study. Two points are less obvious. First, that measurement plays a key role, and the reason is that measurements are the operations by which we enable quantitative representations to descibe phenomena; of course we also make qualitative observations, and these form the links to linguistic reasoning and verbal categories and concepts. We need quantitative representations because material processes and their dynamics are not, in most cases (there are quantum and some other exceptions) categorial in their operation; rather they are matters of covariation among continuous variables (or what amount for practical purposes to continuous variables). The second, and subtler point, is that the actions of the researcher form yet one more semiotic system. Of course our actions are also simply material processes, matter in motion, but more importantly they also have meaning beyond their physical causality, and it is these meanings that allow us to co-ordinate our doings with our other, verbal and visual and mathematical meanings. An operational definition of a scientific quantity is not just a material procedure, it is also a meaningful sequence of actions, which is connectable logically to our verbal definition of the quantity and to its mathematical relationships to other quantities in a theory or model for which we can give verbal justifications in relation to the kinds of human problems these quantities and relations are useful in solving.

solving.

There is, finally, what I believe is a very deep and profound relationship between typological and toplogical meaning-making, one that depends on the organization of human action in the environment at various scales of space and time, and which represents a principle of alternation in kinds of meaning across levels of scale from the molecular on up to the social and ecological. But that is a much larger subject and far from the central themes of my argument here (see Lemke 1998c).

I hope that I have at least persuaded you that if the goal of science education is to empower students to use the forms of reasoning and action that constitute scientific practice, and if the media of communication by which we teach, and the nature of the scientific concepts we hope students will learn to use, are in all cases complex integrations across language, mathematics, visual representations, and practical actions, that it is important to pay much more attention in our teaching to all the languages of science.

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