MULTIMEDIA DEMANDS OF THE SCIENTIFIC CURRICULUM

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ABSTRACT

Close examination of records of student participation in the post-compulsory science curriculum, including videotapes, student notes, teacher handouts, overhead transparencies, and textbook selections, suggests that the maximal literacy demands of the scientific curriculum arise from the need to integrate specialized verbal, visual, and mathematical literacies quickly and fluently in real time. The resulting ‘multi-literacies’ co-ordinate meaning-making activity across multiple media, modalities, semiotic systems, and hybrid genres of communication and representation. After outlining theoretical issues and useful methodologies for analyzing such complex multi-literacy practices, and describing in some detail a number of representative examples, the report considers the implications of these literacy demands for curriculum design, pedagogy, assessment, and research.

Multiple Perspectives on Multiple Literacies

Students in the final years of the secondary curriculum must meet stringent demands for mastery of multiple literacies at an advanced level. From close examination of the records of classroom literacy activities in this project I conclude that not only must students master each separate disciplinary and media literacy at a high level, but they must also learn to co-ordinate and articulate multiple literacies simultaneously. In fact this multi-literacy is itself the primary tool they need for learning; how well they master it may well be decisive for their academic success. Nowhere is this more clearly demonstrated than in the scientific curriculum.

'Scientific literacy' can mean two quite different things: a familiarity with basic scientific facts and concepts, or the ability to use the complex representational apparatus of scientific reasoning, calculation, and practice. Professional science, today as for the past few centuries, makes extravagant use of not only a technical verbal language, but also of mathematical, graphical, diagrammatic, pictorial, and a host of other modalities of representation (Lemke, in press-a). What is special about the use of these multiple modalities in natural science, and to only a slightly lesser degree in mathematics itself, is that scientific concepts are articulated ACROSS these media of representation. What it means to be able to use a scientific concept, and therefore to understand it in the way that a scientist does, is to be able to fluently juggle with its verbal, mathematical, and visual-graphical aspects, applying whichever is most appropriate in the moment and freely translating back and forth among them.

A more critical analysis suggests that it is only in the integration of these various aspects that the whole concept exists. Unless one is among the last of the living Platonists, it is clear that there are no Ideal concepts independent of all possible representations. We can no longer see each possible representation as some partial shadow of an Ideal; there is no transcendental concept to guarantee the unity of all representations a priori. So we do not have so much an exact translatability among verbal statements, mathematical formulas, and visual-graphical or material-operational representations as a complex set of co-ordinating practices for functionally integrating our uses of them (cf. Lynch & Woolgar 1988; Lemke, in press-a). And these co-ordinating practices must be learned in each case as a difficult and specialized form of multi-literacy.

I hope it does not seem too radical at the close of this century and the opening of the computer era to speak of the ability to make and interpret meaning with symbol systems other than written language as quite literally literacies. Efforts to define literacy today inevitably find that there are no principled distinctions between the use of one sort of symbol system and another (Lemke 1989a). Language can take its material form in acoustic signals, in printed orthographies, in manual signing, in glyphs and pictographs, or in Braille. It is difficult to define writing itself in a way which even limits it to the representation of language (Harris 1995, Lemke 1997), and difficult to define language in a way that excludes its interdependence at the level of semantic meaning with visual imagining and situational contexts of activity (Gee 1990; Lemke 1994, in press-a, in press-b). We certainly 'read' and 'write' musical and choreographic notation. Mathematics has its origins in natural language, extending it for purposes of describing quantitative relations and continuous variation at the same time it re-notates what was formerly written in words (Cajori 1928, Lemke in press-a). It is a form of writing, but what we write with it is no longer quite language (cf. O'Halloran 1996). Even written verbal language is clearly also a visual semiotic system as well as a linguistic one, and we can make meaning with subtle shifts of stroke in handwriting and calligraphy, or with choices of font and typeface in print, and have evolved many complex visual genres of writing, from lists and indented outlines to cross-entry tables and print page layouts.

We cannot in a principled way exclude from the notion of generalized literacy any meaning-making practice that deploys a system of meaning-related material signs. Take it for granted as we certainly do, making meaning with spoken verbal language itself is a core literacy skill in this wider sense. And even speech cannot be reduced to meaning linguistically made, since the many distinctions of voice-quality and pacing of speech and many other 'paralinguistic' features are relatively independent of the meaning relations that seem to be internal to language as a semiotic resource system. It's a good bet that we can't ever make meaning in a way that activates only one semiotic system (language, writing, depiction, gesture, voicing, etc.) at at time, even if we mobilize some unintentionally. This is one reason why there are always more possible meanings in what we say, write, draw, or do than we can ever control.

What then do we see through this semiotic lens when we look at the literacy activities of a student on a typical day in an advanced chemistry and later an advanced physics class? In how many ways is he making meaning directly related to learning chemistry and physics? How many systems of signs does he need to be able to interpret? How many material channels carry symbolically coded information to and from him? In how many kinds of culturally normative meaning-making practices does he participate at the demand of the taught curriculum?

Just for starters, one such 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.

The maximal literacy demands of the curriculum are experienced by students in the classroom when a rapidly paced lesson relies on the close integration of a maximum number of individually sophisticated general-academic and discipline-specific literacies.

Fortunately for most students the literacy demands of full classroom participation vary widely during the course of a single lesson and from one class to another. There are times when a student may be occupied with a single literacy (reading the textbook, writing some notes), or when there is ample time to work through the interconnections of what is heard, seen, and read to discover how the whole presents meanings not accessible from the parts separately. There are other times when no doubt the literacy demand level passes the capacity of most students in the room. Perhaps those moments, if not sustained too long, help to stretch those capacities.

Literacies are always active constructions, whether in interpretive processes or in producing new text. The student recorded in this data did not just listen, look, and read. He also wrote words, chemical formulas and mathematical expressions in his notebook, drew diagrams, did calculations on paper and on his calculator, used a ruler to underline headers in his notebook and mark off episodes of the lesson and its content, annotated handout sheets from the teacher, consulted with his neighbor, leafed back through his notebook and forward in the open textbook, wrote assignments in his diary, spoke publicly to the class and privately to the teacher, and used the spectrograph at the front of the room. He asked and answered questions, deciphered and solved problems, transformed information from one format to another ... and occasionally put his head down on the table he sat at or got up for a stretch. If all these activities sound easy, remember that in each case many of the words are new or unfamiliar, the meanings being made are about strange matters of which he has no personal experience, the diagrams and graphs and formulas may bear only an outline resemblance to any he has seen before, the problems are difficult for his current level of mastery, the subject matter is abstract, and the problems of mutual co-ordination and calibration of all these channels and literacies and activities very substantial indeed.

In the following sections of this report I want to briefly outline some of the techniques one can use to analyze the multimedia multi-literacies of the science classroom, then describe in some detail the range one student's multi-literacy activities, and finally consider some of the implications of these findings for classroom teaching, preparation of students in earlier grades, student assessment, and further research.

Ethnographic and Semiotic Approaches to Discourse and Multimedia Analysis

In *Talking Science* (Lemke 1990) I argued that a large part of learning the conceptual content of science is learning to talk its specialized language and use that language in meaningful ways. Even in the early days of that research I recognized the complex integration of speech, gesture, and diagrams, which teachers used to communicate science to students (e.g. Lemke 1987) and the significant relations between written text and spoken discourse in the classroom (Lemke 1989b). Today I realize more clearly that even the verbal discourse of the classroom itself is often not fully comprehensible without co-reference to visual, gestural, or mathematical representations. Nonetheless, even in science classes, most of the conceptual information available takes the form of language, spoken and written. Consequently, the first priority for any analysis of the literacy demands of the curriculum is a rich and diverse repertory of analytical techniques for text and discourse meaning.

I have elsewhere recently and more extensively reviewed the techniques which I personally use and recommend (Lemke, in press-c) for linguistic discourse analysis. Let me summarize the most salient ones here. In my view all meaning-making, including linguistic meaning-making, necessarily simultaneously makes three kinds of meaning: Presentational, Orientational, and Organizational (Lemke 1989c, 1995). These are generalizations from Halliday's (1976, 1994) analysis of the meaning functions of the English clause (ideational, interpersonal, and textual). In short, Presentational meanings are those which tell something about the world, about a state of affairs or relationship, and which construe in words the doings and beings we wish to present to a listener's or reader's attention. Science is very centrally concerned with such meanings in its curriculum. Orientational meaning shows the stance we take toward our interlocutors and toward the Presentational content of our own discourse: are we distant or intimate, condescending or aloof, do we take what we're saying to be certain or dubious, an important matter or a trivial one? In orienting to others and the content of our own discourse we are also orienting in the social space of alternative discourses about our subject, the space of heteroglossia (Bakhtin 1953;

Lemke 1988a, 1995b): do we oppose our viewpoint to another, ally with it, consider it complementary but distinct, equivalent, etc.? Finally, Organizational meaning is not always recognized as meaning in the same sense, but it is so interdependent with the others that it must be included and indeed emphasized. It is the meaning-making by which we show what goes with what, what are the units, the wholes and parts, the internal connecting relations of our discourse that makes it distinct from a collection of isolated and unrelated utterances or sentences.

For the analysis of Presentational meaning, my primary tool is Thematic Analysis (Lemke 1983, 1990, 1995a). Its premise, derived from my work analyzing classroom science discourse and professional science discourse (Lemke 1990), is that we make meaning by invoking, linking, and modifying relatively predictable and standardized constellations of semantic relations among specific units. Each such constellation I call a thematic formation, and these formations are close kin to what are often called 'concept webs' today in pedagogical terminology. What is distinctive about thematic formations is that they are not about concepts but about language, about semantic units; and they are intertextually valid: the same ones recur from text to text and discourse to discourse. This means that we often find only partial instantiations of these abstracted patterns of meaning, a few pieces of the puzzle requiring us to go elsewhere in our experience to complete the picture that a few words can only, but very definitely, suggest to us. Teachers are masters of these canonical discourse formations, students are trying to piece them together. Teacher talk and textbook text try to be as explicit and complete as they can, but it is just not in the nature of normal discourse to lay out complete formations. We present them piecemeal, and students must always learn to assemble them from the partial statements they hear and read (see Lemke 1990 for extensive examples).

It is possible to make rather helpful diagrammatic representations of thematic formations, with the key semantic terms as the nodes, and their conventional semantic relationships (part-whole, class-instance, agent-action, attribute-carrier, etc.) labeling the lines of a weblike network connecting them together into a coherent idealized discourse (Lemke 1983, 1988a, 1995a). They work quite well for all sorts of expository discourse, perhaps less well for action narratives. They work well for monologues and dialogues, statements and questions, expositions and inquiries, and even conversations. They are ideal for relating classroom discussion to textbooks, curriculum documents, and assessment instruments.

But they do not tell the whole story. When we concern ourselves with interpersonal relationships in the classroom, with the negotiation of power and status, and even with rhetorical strategies for argumentation, we need additional tools. The standard ones I use for interpersonal analysis are well described in Martin (1992) and Poynton (1989) as well as in the classic analysis by Halliday (1994). These encompass and go beyond traditional Speech Act analysis. For rhetorical analysis the theory of rhetorical structures (Mann & Thompson 1988a) works quite well. For heteroglossia and social controversy I have extended the thematic formations method to include both evaluative meaning and heteroglossic orientation (Lemke 1988a, 1989c, 1995a, in press -d). Evaluative analysis seems especially appropriate for such texts as statements of the goals of a curriculum.

Finally, one needs some organizational structures on which to hang all these other kinds of meanings. The largest such structures are Genre structures (Hasan 1984a, 1989; Martin 1989; Lemke 1988b) on which there is a very large literature today, and within them the rhetorical structures noted above, on down to sentence and clause-level structures (see Halliday 1994). But in addition to segmentation structures in which units neatly follow one after the other, discourse and text are also organized by cohesion patterns which enable links to be made across long stretches of text (Halliday & Hasan 1976, Hasan 1984b), and probably the fullest Organizational analysis is one which examines how the segmentation structures and the cohesive textures play off against one another (e.g. Lemke 1995b).

While these may be the most basic methods, there are of course many more. Narrative analysis is a very popular technique, but not of much relevance I find to most science classroom language data. Science suppresses its narrative underpinnings (cf. Lemke 1992). Hasan and Cloran (1990) have developed a very powerful technique of semantic analysis which supersedes speech act analysis, but has thus far mainly been used for statistical comparisons of the dispositions toward different ways of meaning of different groups (by gender, by social class, etc.).

Language, however important in itself and however much we have learned about how to analyze it, is still just one form of action and just one resource system of signs with which to make our meanings. To integrate language into its contexts of situated use, to understand what people are doing with what they are saying, we need to describe more generally what they are up to. This is the problem of ethnographic analysis, and it forms the widest context for all more specific linguistic and multimedia semiotic analyses. For a formal ethnography you need to be on-site for an extended period of time; you observe across the boundaries of different situation types, settings, and activities; you follow the human social networks where they lead; you get to know people and perhaps formally or informally interview them (leading to more discourse data); and you collect the portable artifacts that embody their cultural practices (in classrooms: textbooks, notebooks, handouts, overheads, lab instructions, etc. -- yet more textual data). You write fieldnotes, you take photographs, you make audio and video-recordings and sketches and drawings. You generate, as data for your analysis, a whole host of secondary semiotic records and representations to add to and reinforce your memories of what it felt like to be there, and how those you were visiting said it seemed to them.

Having done all this you will be in possession of a vast archive of data which you will never be able to analyze exhaustively. You sift through it in search of salient patterns, often guided by the differences between your perceptions and those of the people you visited. When you identify a candidate pattern, you look for other instances elsewhere in the data, and very often you then notice still other patterns. These are patterns within language data or visual data or semiotic data of other kinds, and between them. I have just identified various techniques for analyzing many features of the language data. For the other kinds, methods are not yet as well developed or reliable. New work on visual semiotics, compatible with the verbal methods described above and easily integrated with them at the level of meaning, has been done by Kress & van Leeuwen (1996), O'Toole (1994), and Martinec (1997). van Leeuwen's work has particular application to the analysis of diagrams and graphics (see also Tufte 1983), and Martinec's to video-analysis of action. I am developing my own approach to multimedia semiotics which considers both language and visual representations in a functionally integrated fashion (Lemke 1997, in press-a).

Multi-literacy Demands in Chemistry and Physics Class

In this section I want to provide some detailed accounts of how multiple literacies were integrated by a single student (pseudonymously John) in several episodes across his Senior Chemistry and Senior Physics (Year 12) classes on one particular Tuesday.

9:14am. "Skills Testing"

John is sitting at the end of the second-from-front row of tabledesks used by students in this Chemistry class. His teacher, (psudonynously) Ms. Cramer, has lost no time getting down to the first order of business: letting students know exactly what they will be responsible for on the upcoming basic laboratory skills test. She has distributed a review sheet to everyone with 35 specific items in 6 different categories, and she is rapidly quizzing students on selected items (using the IRF or triadic dialogue procedure; cf. Lemke 1990). John has the sheet in front of him, pen in hand, and is listening to her questions, other students' answers, and her confirmations whether they're correct, while annotating his copy of the sheet with notes such as "read", "Pb Cu Zn Ag ...", "LEOA GERC", and at the bottom "conc - acid 20mins".

At first sight John does not seem to be doing anything very complex, but in fact he is co-ordinating: (1) a complex listening skill that requires him to synthesize from at least three different utterances by two parties to a dialogue one single correct proposition, (2) reading and interpreting the genre of an outline-format text in which he must infer the semantic relations between a header such as "Identifying" and an item under it such as "precipitations and saturated solutions", (3) writing elliptically in a way addressed to and recoverable by himself additional information he extracts from (1) and decides is not adequately represented in (2). As if this were not enough, both the students and Ms. Cramer are at various times during their review dialogue using complex gestures to indicate operational procedures such as how to position your viewing eye in sighting for a measurement or how to hold a piece of apparatus properly.

Later, when John wants to decipher his annotations in relation to the layout of text on the review sheet, he will have to reconstruct meanings such as the fact that "read" written next to "burette" means he's responsible for being able to read a quantitative measure from a burette rather than that he needs to read the discussion of burette in the textbook. He uses visual notations such as a multi-line-spanning curly bracket to indicate that his notation "Units for all" means that for items 1-9 he needs to know the units of measure that are customary for each measuring instrument listed. When he writes "Pb Cu Zn Ag ..." he is translating the teachers spoken English names of these chemical elements automatically into their standard chemical symbols, which in cases like Pb for lead have no phonetic or orthographic relation to their English names. When he writes "LEOA GERC" he is reminding himself of mnemonic acronyms for what happens at the anode and cathode of an electrochemical cell, and his notations at the bottom of the page summarize a short statement by Ms. Cramer about how long you should flush concentrated vs. dilute acids from your skin after an accidental spill.

In all this substantial amount of written technical information, there are only three complete normal English sentences, all minor addenda to the main body of information. The teacher has written a peculiar curriculum genre that begins a sentence, erects a colon, and adds in indented outline format various further dependent clauses and multiple lists of alternative clause-elements in such a way that a practiced reader could construct a great many independent sentences from this verbal matrix. This is an advanced literacy skill for reading. It is required by the specialized conventions of an unusual genre of writing that is probably not actually taught in the preparatory curriculum. It is probably not even much taken notice of by the curriculum designers who write this way themselves every day. John has not written any sentences, indeed nothing more grammatically explicit than a few 2-3 word noun phrases ('Units for all' 'dilute acid'), and yet he and we can reconstruct a very substantial amount of propositional information even from his one-word and symbolic abbreviations. How? By making use of our tacit knowledge of the intertextual thematic formations (above) which we know to be applicable in this particular context. This, too, is an advanced literacy skill which is not normally taught. At the rate Ms. Cramer is reviewing this material, John would not possibly be able to write out complete sentences and still keep up. Nor would it be normal for him to do so. He has at his command many alternative literacy techniques, including several specialized to the subject of Chemistry (e.g. the use of chemical symbols) .

Except for its rapid pace, this first episode was relatively minimal in its literacy demands on John. Things soon get still more complicated.

9:38am. The Uses of Salts.

Ms. Cramer is projecting an overhead transparency (hereafter OHT) on the screen at the front of the room; it lists in a column down the left side 13 formulas for chemical compounds, all of them the salts of common acids and bases (when an acid and base neutralize each other what's left is water and their compound salt). John's task at this point is to complete as much as he can of an empty Table of which the Salts form the first column, their Uses the second, and their Scientific Names the third. After a while Ms. Cramer will start asking students for answers and filling in the Table by writing on the blank space of the transparency. What does John do?

First he copies all the formulas for salts just as they are on the OHT. He is copying them onto a page of his notebook, which lies open before him. This is as low a level of literacy demand as he will have in this class. It is in itself no small feat, given the complexity and unfamiliarity of a symbolic notation which criterially distinguishes upper vs. lower case letters, subscripts vs. on-the-line numbers, and the use of a raised dot before showing linked water molecules bonded weakly to the salt proper (hydrates). But John has spent months learning to be at home with this particular literacy. He proceeds to confer with his neighbor, (pseudonymously) Nick, about the answers. He flips through his textbook briefly, then sees that Nick has his own textbook open in his lap and turned to a page that contains most of the answers (Wilbraham et. al. 1987: 458), also in a Table. After a few minutes he opens his own book to this page and begins to work rapidly by himself.

Table 19.1 in the book is a little different from the one Ms. Cramer is constructing. It also uses three columns, but the first is the Name, then the Formula, then Applications. The salts are not in the same order as on the OHT and in his notebook, and there are more salts in the book. John has to match the formulas to identify the relevant row of the Table, being careful not to confuse many which are identical except in one small detail (a letter, a number); he can then copy items from corresponding columns. What he has written in his notebook under Uses, however, does correspond exactly to what's under Applications in the book. In some cases he is simplifying, taking one item instead of two, or shortening a phrase to a word. And in this he must make a judgment that he is conserving what's essential.

Ms. Cramer begins her discussion of the Table with the class long before John is finished. Now he must again listen to questions, answers, and evaluations of answers, sometimes involving disagreements and questions, extract key words as well as names and write these in his notes. He is now co-ordinating: reading the book, interpreting and at a couple of points participating in the oral discourse, reading what Ms. Cramer has written on the OHT, and his note-taking. For each there are specialized genres: the triadic dialogue genre of the discourse, the Table genre of the book, OHT, and notes. If you think this is trivially easy to do, I suggest trying it. Both John and Ms. Cramer had lapses during this multi-literacy process. Ms. Cramer, in preparing the OHT, had miscopied one of the hydration coefficients from the textbook. John has carried her mistake over not only in column one, but has consequently misnamed the compound in column three (copper sulfate hepta- vs. penta- hydrate). Even his misnaming was a literacy achievement however since Ms. Cramer, in speaking of this compound, abbreviated the name and omitted the 'hydrate' part, and John took the 'heptahydrate' from another compound in the list which had the same (in this case correct) hydration coefficient, expressed as a number. John had also already written "antacid" as the Use for sodium bicarbonate, and when he catches Ms. Cramer saying it's used in cooking, he writes 'cooking' in his notes, but in column 3 under the Name, not in column 2 with "antacid". Small lapses, but indicative that co-ordinated multi-literacies like these push the limits of our information-processing capacities at the rate at which this lesson was paced.

My initial judgment of Ms. Cramer's pacing here was that it was admirable in terms of covering a lot of simple material quickly. I compared it favorably with the slower pace of both John's other teachers that day (in Mathematics and in Physics). But now I am not so sure. I still think her pacing was appropriate, but perhaps not as ideal as I was inclined to believe. Ms. Cramer did not slow down much later in the lesson when new and difficult conceptual material was being presented. I know the pressure teachers are under to cover an overstuffed syllabus before an unforgiving examination; leeway in pacing may be minimal. It is the curriculum that is often at fault.

John and his classmates next get a rest. For about 5 minutes they are to read a rather dull passage on soil chemistry from the book (Wilbraham et al., 1987: 459-460). John does so, has a little dialogue with Nick, and makes rather good notes. I will not analyze this process, though comparing the original text with John's notes through thematic formation analysis (above) would enable us to identify exactly what strategies were used for semantic selection and written condensation of the passage's content. I will note one feature that distinguishes the literacy demands of this task from the more usual reading and note-taking that is, to some degree, explicitly taught in the preparatory curriculum. This 5-paragraph text contains chemical ion symbols interpolated into the text as if normal lexical items of English and one typographically set-off line of a chemical reaction equation of some complexity. Its relationship to the rest of the text is in no way verbally indicated in the text itself, but must be inferred by a specialized genre convention for scientific writing (which has actually been violated here, probably by a copyeditor who changed a usual colon to a misleading period or full-stop mark). The actual connection of the equation to the preceding and following text is complex and requires integrating mathematical and chemical notations at the semantic level into the thematic formation analysis. This actually presents new theoretical issues, some unresolved (cf. O'Halloran 1996).

John's rest period is soon over. From about 9:52am onwards Ms. Cramer leads the class through a progressively more complex series of concepts and examples in acid-base chemistry. The multi-literacy demands here reach very high levels in which there needs to be simultaneous attention to and co-ordination of literacies of interpretation and production for several specialized genres of classroom discourse, textbook reference, OHT interpretation, note-taking, calculator calculations, and chemistry problem-solving. The following is one such episode that is representative of the maximal multi-literacy demands on John in this class.

10:08am. "What is the pH ...?"

Ms. Cramer puts up OHT #5, indicating that we are moving on to the next chemistry problem, one that will prepare students for the concepts of ''equivalents' and 'normality', which adjust our measures of the strength of an acid or base not just for the concentration of its active ingredients in a water solution, but also for how effective each of those agents is as an acid or base. The OHT presents a simple statement of a problem:

5. 15.0 mL of 1.0M $NaHC0_3$ are added to 30 mL of 0.8 M H_2SO_4.
What is the pH of the resulting solution?

John reads this from the overhead, then listens as Ms. Cramer comments on the problem and asks the class first to write out the complete chemical reaction and then see what they can do with the problem. John already has his calculator out. He confers with Nick and writes out the chemical equation for the relevant reaction. He flips back through his notebook about 10 pages to look something up (perhaps the definition and formula for pH, which he will need). I believe, watching the tape and examining John's notes, that he has written down at this point the outline of the chemical equation, meaning he has correctly predicted what chemicals will result at the end of the reaction. He has not, however, worked out the 'balancing' of the equation, which tells quantitatively the ratios in which the chemicals combine and are produced proportionately to one another. He appears, from the look of his notes, to have added these later as they were worked out in the class discussion. John has written the chemicals in the equation in his own order, not that which Ms. Cramer uses, indicating he did not copy it, but anticipated it on his own. But the quantitative coefficients appear to be added in a different pattern of spacing of symbols from that of the skeletal equation.

Once the fully balanced equation is now up for all to work with, John has some more time, and confers with Nick and looks in the textbook, but does not write down any conclusions. Ms. Cramer and the class resume discussion and she indicates the next step, to calculate the total numbers of molecules (in a large standard unit of counting called a 'mole') of each initial ingredient (reactant) in the mix. John now speeds ahead, using his calculator, setting up the calculation on paper in his notebook in a variation of a standard visual layout genre, and coming up with the correct answer for the first, and then the second reactant. He is co-ordinating listening to and participating, somewhat unofficially (he murmers answers in a non-public voice, is not called on to answer officially), in the discussion, using his calculator, writing the problem format and answers in his notebook, and conferring with Nick.

What adds to the literacy demands at this point is not the number of different channels and specialized genres he must cope with, but the complexity of integrating verbal, chemical-symbolic, and mathematical meaning systems across genres that depend as much on visual layout as on linguistic syntax or vocabulary meanings for their sense.

The key new conceptual step in this problem comes next. Ms. Cramer asks "Which one is in excess?" This means, after complete neutralization of one reactant by the other, which one has a bit left over? This would be trivial if they reacted in a one-to-one ratio, but in this case they don't. The ultimate answer, the pH, will depend on getting this right. Ms. Cramer and some of the students discuss this and on the overhead Ms. Cramer writes, as she might on the chalkboard:

0.015 + 0.024
0.015 + 0.0075

If this has been transcribed properly in the data set, either she has made a mistake or she indicated verbally some quite unobvious relationship among these numbers. In fact, John has sorted things out fairly well, but also not quite perfectly. He has written one pair of numbers above the reactants in his equation (with the order properly reversed since he had originally listed them in the reverse order)

0.024 0.015
H_2SO_4 + $2NaHCO_3$
0.015 0.0075

but he has not reversed the order of the numbers written below, and they would not have been right even if he had since they seem to be wrong on the OHT as well. Both Ms. Cramer and John seem to be using an algorithm based on a visual layout model here. It says to write the amounts (in moles) above, and then write below the reaction formula the result of dividing these numbers by the coefficients of each reactant, here by one for H_2SO_4 and by two for $NaHCO_3$. On this reasonable assumption, what Ms. Cramer (or the data transcriber) should have written is:

0.015 + 0.024
0.0075 + 0.024

and John should have:

0.024 0.015
H_2SO_4 + $2NaHCO_3$
0.024 0.0075

The difficulty here, apart from the concept itself, is that Ms. Cramer's lines of numbers only make sense in the context of her verbal description of what she is doing and what they refer to as she writes them. If any of that is missed or misinterpreted, the written numbers themselves are useless. Nowhere is division by two written, nowhere is the reason for it written. Ms. Cramer does describe the reason verbally and emphasizes the significance of the fact that the "reactants ratio is two." I can only assume that this algorithm is supposed to be already familiar to the students, but clearly not familiar enough yet for John, and complex enough that even Ms. Cramer may have slipped up.

From this point on John simply copies what Ms. Cramer writes, so the next step shown is to subtract (0.024 - 0.00175) to get the excess. Next she and the class in discussion set up an equation to find the pH from the excess. Once the problem is set up to the point of finding the number of moles of hydrogen ions resulting from the excess, John again takes up his calculator and moves ahead of the discussion to reach the final answer. The calculator is necessary here since John has to use it to find the logarithm of a particular number, which cannot easily be done in any other way. He also must both interpret correctly the problem-solution visual layout on the OHT and set up another such layout to guide his calculation through several steps to the the final pH answer. John's layout at a certain point diverges from that on the OHT (which represents Ms. Cramer's model), as you can see by comparing Figures 1 and 2 (appended).

At one point or another, co-ordination among the various literacies in this episode has been necessary and not merely optional. John could not have successfully gotten the information he needed from just one channel of communication, by a single literacy appropriate to a single genre. He needed to combine interpreting the verbal discussion with reading the visual layout on the OHT for the algorithm. He needed to coordinate the use of the calculator, the verbal steps of problem-solving, and the visual layout of the calculator in order to move ahead of what Ms. Cramer was writing. He would also later have needed to compare (itself an integration) his solution and hers, not just in terms of final result, but in terms of correctness of method, represented solely in the verbal interpretation of the visual layout of the mathematical calculation, including its chemical symbolic notation.

The high demands of co-ordinated multi-literacy here arise from the multiple semiotic systems (verbal language, mathematics, chemical symbolics, visual layouts, specialized actions), the multiple genres (triadic dialogue discourse, written text, chemical reaction equations, various calculational and problem-solving algorithms visually laid out, calculator procedures), and the degree of specialization and sophistication of each of the distinctive literacies needed to cope with these genres. Above all, they arise from the more complex kinds of meanings that can be made, and in science are necessarily and only made, by the integration and coordination of more than one, and quite often more than a few, of these literacies simultaneously.

The complexity of the last episode is not at all atypical. It runs through most of John's Chemistry lesson. Nor is it a peculiarity of Ms. Cramer's teaching style. We will find it again in John's Physics class this afternoon, and with several additional semiotics and genres and specialized literacies which he needs to integrate and coordinate to make sense in today's other science class.

Interlude: Math and Lunch

Chemistry class was pretty much a non-stop information-processing workout this morning for John. Ms. Cramer did let the class off the hook in the last 15 minutes. She did not stop providing a steady stream of information they need to pay attention to, but at least they did not have to take more notes or try to work problems on their own or be held publicly responsible for answers. Chemistry lasts from 9:05 to about 10:40. It is followed for John on Tuesdays by Senior Mathematics B. Today they are discussing the use of public surveys as a context for using the mathematics of elementary statistical distributions. They don't really get to the distributions, and this particular lesson is more about social science research methods than about mathematics as such. The pace is very slow compared to what John has just been through in Chemisty; the teacher has the students read and discuss with their neighbors longish textbook passages and answer rather simple questions, also from the book. He comments and asks a few leading questions of his own, prompting the students to relate the topic to their own knowledge and experiences. The literacy demands are not simple, but they are relatively minimal compared to much of the rest of John's day. I will skip over this period. It is not typical of the teaching of secondary school mathematics at an advanced level. John got off very easy today for well over an hour in Math. He then had another hour for Lunch. John needs this break. But soon Lunch is over and now it's time for Physics.

1:40pm. "Energy levels"

It's the beginning of the lesson. John is listening to his Physics teacher, (pseudonymously) Mr. Phillips, remind the class about different "ways to excite electrons to higher states". John can make sense of this in terms of a particular thematic discourse formation of physics in which 'higher' in this verbal context means 'higher energy' and 'excite' means 'give energy to' the electrons. John here needs a sense of 'higher' as 'quantitatively greater', but it may be combined with the sense of 'higher up' on a diagram of potential energy, itself modeled after higher in altitude above the surface of the earth (and so higher in gravitational potential energy). He needs to know that gravity and altitude are just analogies in discourse about electrons (whose potential energy in an atom is electromagnetic, not gravitational). Issues of quantity and spatial representation of energy in diagrams are about to become very relevant for John. If he hasn't been half-thinking about these matters from the start, he will soon need to be doing so.

John watches Mr. Phillips do a demonstration in which a glass tube filled with hydrogen gas has an electric current run through it and glows with emitted red light. He and Nick comment to each other about the demonstration as it take place. Mr. Phillips explains what is happening in terms of electrons and energy levels and how the light from the tube can be analyzed spectrographically to find the numerical values of the energy levels of electrons in hydrogen atoms. At about 1:50pm he tells them that in physics we use "mathematics to simplify data" about these energy levels and he writes Bohr's formula on the blackboard:

$$E_n = E_i - E_i / n^2$$

He dictates notes and John begins to write. In his notebook he first uses a ruler to create a Header "Energy Levels of Hydrogen" with widely spaced words and double ruled underlining, centered on the page. There is no syntactic or textual link of this Header to what follows it, but its meaning relationship as a context for what follows it is critical and demonstrates John's literacy about the visual semiotics of page layouts. John writes "Bohr -- found energy levels for hydrogen can be calculated using ..." and he underlines "Bohr" once and writes the formula on a separate line, followed, as Mr. Phillips does, by "where" and three lines defining, with equals signs, symbols in the formula as equal to word phrases like "ionization energy". He is now integrating and co-ordinating: listening to Mr. Phillips, reading from the board, and writing using the literacies of visual page layout, verbal language, and mathematical formulas. Nothing in this yet involves numbers or quantities; everything could be read out in standard English, though probably John would read it as Mr. Phillips does, using English syntax (mostly) but substituting the names of mathematical symbols for English words. This is itself still another specialized literacy, like reading chemical formulas out loud, knowing how to translate them automatically between read-out symbols and word-like names, or speaking numbers like "oh-point-oh-one-five" or "zero-point-zero-fifteen". This is the literacy we use to make sense of: "Ee-en equals Ee-aye minus Ee-aye over en-squared", which can usually only be successfully done by visualizing the symbol pattern of the corresponding algebraic equation (and so, for example, distinguishing whether the 'over-en-squared' modifies only ee-aye, or all of ee-en minus ee-aye). Also used here is the specialized mathematical-visual-display genre pattern for a formula with its specification of variables by 'where' or 'in which' statements.

John soon hears Mr. Phillips ask the class to find the numerical value of Ei, the ionization energy for hydrogen, and he turns to his textbook and mobilizes the literacies needed there (Storen & Martine, 1987: 548) to locate the not very visually prominent value of 13.6 eV. He then takes up his calculator and begins to put in values of n, starting with 1, 2, 3. Here he briefly gets ahead of Mr. Phillips work at the board, which fixes the results of his question-and-answer discussion with other students, which John is also listening to. The answers are on the next page of the textbook, along with two complex energy-level diagrams. Mr. Phillips is putting a similar simplified diagram on the board and John is copying it into his notebook. Mr. Phillips also introduces a second version of the diagram and draws it, as well as both explaining the relationship betwen the two versions and dictating what the students should write in their notebooks in between the two to explicate this relationship. John writes: "OR -- If we take the zero of energy as ionization energy: -- " below the first diagram and directly above a revised version of the Bohr equation, and then next below it, the second diagram. Here we see diagrams and equations introduced as textual elements linked by the English conjunction "or", and introduced by a colon. Doing this requires an integrated and genuinely multimedia literacy as well as a multi-semiotic one and a multi-genre one.

To confirm the point about integration note that not only are diagrams and formulas treated as quasi-linguistic elements of the text, but each diagram consists of not just visual elements (lines, angles, shadings), but also contains numerical labels, and even labels like "n=2" which are mathematical formulas (and equivalent to English sentences), as well as one label "ionization" which is an English word forming an integral part of a diagram. Language, visual depiction, and mathematics are fully integrated here in a multi-semiotic genre that is a composite of, or perhaps better a hybrid between other genres (expository text, graphical diagram, mathematical derivation). Perhaps the preparatory curriculum has explicitly taught these separately as pure idealized genres, but how far has it taken students toward understanding what happens in these very common hybrids?

Classroom discussion; teacher exposition; blackboard and notebook mathematics, writing, and diagrams; numerical calculations on paper and with a calculator; and a few odd gestures of significance. Integrated by their simultaneity and timing, by their visual juxtapositions, by their syntactic and semantic relationships, by their operational sequences (write, draw, calculate, write) and linkages. Write in English, write in mathematics, integrate these on the page and in inner speech. Make sense multiply, simultaneously, inter-operably. And don't forget the demonstration, the way the wires and apparatus were connected, what you saw and how it was linked invisibly to what Mr. Phillips was saying at certain precise moments. Those words are the only link between the demonstration and the writing on the board, in the textbook, in my notebook. A process I will have to reverse when I go up later and operate the apparatus myself.

2:06pm. "Absorption spectra"

It was diagrams and mathematical formulas that mainly integrated with language in the previous episode. In this one and the next it is gestures and mime that require additional hybrid multi-literacies on John's part.

At the blackboard, Mr. Phillips is gesturing in the space of a diagram of the apparatus of an absorption spectrograph. John has copied this diagram into his notes. He must learn about the processes that take place here, the dynamics of what happens in this apparatus, by watching the movements of Mr. Phillips' hands as he narrates the workings of the machine. A static diagram cannot easily show these processes, only parts and places (though arrows are sometimes used to imply process through movement). John understands the relations of the parts of the apparatus fairly well because Mr. Phillips also narrated their functional relationships as he drew the diagram, from the right side to the left side, element by element, working his way backwards from the outcome (what the students can see looking into the eyepiece of the apparatus) to the source of what they see. Gesture, diagram, and language interpretation must fuse seamlessly to make these meanings.

Now John sees Mr. Phillips come forward toward the rows of seated students and stand in place, continuing his exposition, with occasional questions to students. He is explaining how an absorption spectrum looks. It consists of vertical lines, and he draws these lines in the air with vertical downward gestures of his raised hand. He goes back to the blackboard and John sees him draw a very simple schematic, a long rectangle of chalk, and vertical white chalk lines inside it. But John hears him say as he draws the rectangle that it is "a spectrum of colors" from "red ... to blue" and sees him point to the left end when he says red, the right when he says blue. The lines are described as "dark" against the rainbow background of this spectrum -- exactly contrary to the black chalkboard background and the white lines he has drawn. But John understands this, and more so when he sees a second rectangle, also with lines, but labeled as an 'emission' spectrum and hears Mr. Phillips saying "most of you expected to see" something like the bright emission lines (diagram 2), but what we do see are the dark absorption lines (diagram 1).

Mr. Phillips goes on to talk about how the earth's atmosphere imposes absorption lines on the spectrum of the sun's incoming light, and how we have to learn to "match up" the emission spectra (like that of the hydrogen tube at the start of the class) and the absorption lines, and he mimes holding glass-plate spectrographs by their ends and putting one up on top of the other, superposing them imaginarily in the air, just where he had previously drawn the individual imaginary spectral lines with his raised hand.

Language, diagrams, gestures, pantomime -- all working together to make meanings that are quite different from what they might seem to mean in isolation. Each modifying and even reversing the meaning values of the others, in combination. Interpretable and writable only through specialized multi-literacy skills.

2:50pm. "Laser Light"

As a final example, and one in which 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, consider how John learns about the principle of the laser.

Mr. Phillips is standing just in front of the first (empty) row of student desktables, at the opposite end of the room from where John is sitting. John sees his 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. 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.

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 the laser beam then? He walks back and forth between the ends of his now lasing imagninary 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. 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.

Mr. Phillips also uses gestures in a less pantomimed way. Gestures segment and emphasize elements in his speech stream and co-ordinate the timing of his words with other motor actions visible to the students. A gesture underlines "most of" when it's important. A gesture reinforces "organizes" and seems to be iconically corralling something together. John is also used to incorporating this kind of information in making sense in physics class.

Mr. Phillips will go on to demonstrate a laser, to dictate notes to the students about lasers, to give them information on a hand-out sheet. John will retrospectively integrate these other media of information with his first impressions gained from the pantomimed and narrated explanation.

Conclusions: Curricular, Pedagogical, and Research Implications

I hope I have made at least a credible prima facie case for the centrality of multiple, integrated, and co-ordinated specialized literacies across different media of communication and semiotics of representation in the post-compulsory scientific curriculum. I hope I have started to show the importance of hybrid multi-media genres and their associated genre-specific literacies, even without considering video or computer-based multimedia. I have tried to focus on the maximal literacy demands of the curriculum and found that demand peaks when more different media, semiotics, genres, and specialized literacies must be co-ordinated and integrated at a relatively rapid pace. To be successful in the post-compulsory scientific curriculum students must become relatively fluent in these multi-dimensional, multi-modal literacies. Many students do not.

The pace of curriculum delivery is not just a function of pedagogy. Teachers may talk, write, draw, mime, gesture, show, and calculate faster or slower as a matter of individual style. What matters more is how much pressure they are under to present how much conceptual and factual content in a fixed number of contact hours with students like John. What matters to John is how new and unfamiliar each communication is; how much redundancy with previous learning there is; how much he can count on what he already knows to help him take each next step. Too many steps, each too big, all to be taken too quickly, will lead to a stumble -- or to dropping off the pace, and maybe even out of the race. Students like John are doing pretty well, but how many others never entered the post-compulsory curriculum, particularly in scientific and technical subjects, because they felt they were already past the limits of their ability to handle the multi-literacy as well as the content demands of the prior curriculum?

Effective pace must be understood relative to the rate of production of novelty. We can very rapidly review well understood material; we can very rapidly repeat familiar exercises. What is new requires more time and patience, and this is true not just of content, but of the specialized literacies that must be acquired too often as a merely implicit part of that content. This is also true of the interaction between novelty of content and complexity of literacies required for making sense. Curriculum designers need to examine carefully which specialized multi-literacies and hybrid genres are actually required in practice, determine when they should be taught explicitly (still in the context of content learning, of course), and take them into account in figuring the total learning burden per week or per month which a curriculum imposes on students. Then and only then will teachers be in a position to adjust their pedagogy, including their pacing, to the total learning demands of the curriculum, including both specialized content and specialized multi-literacies.

At the pedagogical level too, it is very valuable to look at things, as we have been encouraged to do in this project, from the student's point of view. This type of analysis will show that individual students have a considerable range of strategies for coping with the literacy demands of the curriculum and that they vary these strategies from episode to episode, class to class, day to day, and year to year. Some have more varied and better mastered repertories than others; some are more comfortable with some strategies than with others. Pedagogy demands comparable outcomes from all students, but it must not also demand identical strategies and pathways to those outcomes. All development, epigenetic and educational, has an element of equifinality to it. Cultures and environments produce from a diverse subcultural and gene pool individuals who are still remarkably alike as a species or a social group, but if we follow individuals, we will see that no two get to be similar in the same way. For these reasons, pedagogy must respect the principle of redundancy in communication: it must be possible for students to get the same information, concepts, and understandings through different channels, different media, different multi-literacies. This does not simply mean more repetition, nor even more varied media of communication (they are plenty varied enough as it is!). It means that the same information, or elements needed for the final synthesis, have to be accessible through as many different combinations of media as possible.

It is not theoretically possible to code all the ideas of chemistry or physics just into language alone. It is not in the nature of these disciplines' practices. Nor could we do so even just into mathematics, or just into diagrams. All the possible literacies of these disciplines are multi-literacies. What is possible is to put some ideas across in both a verbal-visual and in a verbal-mathematical way, as perhaps also in a visual-mathematical way, as well as obviously through all three modalities together. At this high level of abstraction there may seem to be a limited number of such combinations, but as we have seen in this report, every different hybrid genre and mix of hybrid genres effectively calls forth its own specialized multi-literacy, even though it may be analyzed as having been built from more widely used components. (It's one thing to have seen such a component somewhere else; it's another to know how to integrate it into the current mixture.) Teachers can multiply genres and try to make sure that contrary to current practice, in which it often requires every single piece of the puzzle to make one single whole picture, the picture can be made from many different possible subsets of the many pieces provided: a jigsaw that enables us to make the same picture many times over, in many different ways, using less than all the pieces provided. Much easier as a puzzle, but the picture is still seen, and seen by more students.

Multi-literacies and hybrid genres should be taught. What I mean by this is that both teachers and students should be made consciously aware of their existence: what they are, what they are used for, what resources they deploy, how they can be integrated with one another, how they are typically formed, what their values and limitations are. This is not so much a matter of adding a whole new strand to the curriculum as it is of foregrounding and thematizing what is already in the curriculum, getting teachers and students to pay attention to what was formerly taken for granted. Doing so would help teachers plan for redundancy and for pacing, it would help students see more clearly what is expected of them for success, it would enable all of us to take a reflexive look at these genres and multi-literacies and evaluate them critically and thoughtfully. It would also add real substance to otherwise rather nebulous prescriptions for more emphasis on 'meta-cognition'. Most of what meta-cognitive practices must attend to, or at least the parts that are accessible to to examination and revision, are precisely the ways we make meaning with real genres deploying the semiotic resources of language, image, quantity, relationship, gesture, and action.

We already test, too implicitly, for multi-literacy competence. As with the implicit role of these specialized multi-literacies in the curriculum and in pedagogy, in assessment also there is a need for more explicit awareness and practice. I do not advocate direct testing of these advanced skills. They are too completely integral to the genres (including the action genres) where they are needed to be validly tested in isolation. They are also strictly bound to the kinds of content and meaning issues which those genres have evolved to deal with. But assessment designers do need to be more fully aware of the kinds of integrated literacies which any given assessment task or activity presupposes. They need to take into account the role which multi-literacy demands will play in determining the difficulty of and the time needed to satisfactorily complete various tasks. They should also, if possible, design assessment tasks which can be completed by various different combinations of literacy strengths, unless they have the specific charge to assess a particular multi-literacy skill.

Finally, we come to the need for careful further research into the multimodal literacies and genres of each specific curriculum subject at each grade level. This is beginning to be done in many places today with regard to the simplest forms of reading and writing, but with still far too narrow and idealized a view of what literacy-in-practice actually involves. Literacy in the real world, as in the advanced curriculum, is always multiple and integrated. We never read without some visual images or kinesthetic modelings, we don't use mathematics or diagrams without language intervening. Writing is always a visual meaning system as well as a linguistic one. We always create styles and emphases and organizational cues through visual as well as verbal means. Sometimes these are very simple, but often they can be amazingly complex. The scientific and technical curriculum is a good place to begin the work of specifying relevant multi-literacies in detail. Its genres are so specialized and unfamiliar except to experts that their multi-literacy demands tend to stand out. We need research to support curriculum design that will tell also us more generally what these relevant literacies and genres are, across semiotic modes of representation and across channels of communication, for all curriculum subjects. We need even more basic research on how people in fact integrate very different media. What have been the origins and histories of these hybrid genres? What educationally useful alternatives may have been lost or missed? What are the general functional bases for the very possibility, the almost universally felt desirability, of integrating different modalities? How have the different modalities of representation co-evolved with one another culturally and historically in the various disciplines? How is spoken language itself already pre-adapted to be integrated with gesture, and writing visually integrable with diagrams?

There can be no doubt that as computer-assisted education becomes more and more widely available, in the home as well as in the school, issues of teaching and learning through integrated multimedia will become even more important (cf. Lemke 1996, in press-b). If nothing else, computer media will spawn new hybrid genres (e.g. hypertexts, interactive media, 3-dimensional scientific visualizations, dynamic simulations) that will require the development of still more multi-literacies. Research will need to continue to analyze these as they arise and must help keep the curriculum prepared to make use of them and help keep teachers and students up-to-date in their abilities to meet the total literacy demands not just of the post-compulsory curriculum, but of careers and lives in the 21st century.

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FIGURES