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ABSTRACT

This review brings diverse research to bear on the contention that current achievement tests may underestimate students' subject-matter knowledge and problem-solving ability because of the mismatch between the symbolic form that typical achievement tests use and the specificity of students' symbolic encoding that arises from instruction and individual differences. More specifically, the possibility that alternative representations of science problems affect achievement estimates is examined for students varying in socioeconomic and ethnic/racial backgrounds. Theory and research are examined for the effects of symbolic encoding on information processing and the effects of translation among symbol systems on problem solving. Testing with alternative symbolic representations is placed in the context of the literature on minority group testing. Research on minority group testing has rarely focused on the possibility of alternative symbolic forms of tests or test items. There has been little attempt to determine the strengths of particular cultural and language groups and to develop tests that capitalize on them. Instead, research on minority group testing has concentrated on: (1) the validity of group differences in test scores (test bias); (2) the testing of linguistic minorities; and (3) the development of culture-fair tests. A 70-item list of references is included. An appendix describes the development of a taxonomy used in science textbooks to present concepts of heat and temperature. (SLD)

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on Evaluation, Standards,
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ALTERNATIVE STRATEGIES FOR MEASURING HIGHER-ORDER SKILLS:

THE ROLE OF SYMBOL SYSTEMS

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Problem solving in many subject-matter domains often requires the problem solver to transform a problem from its original symbolic representation (e.g., words) into an alternative symbolic representation (e.g., iconic, mathematical) in order to arrive at a solution (Clement, Lockhead, & Monk, 1980; Hooper, 1981; Nesher, 1982; Shavelson, 1981; Shavelson & Salomon, 1985). Consider, for example, the following word problem: "Start with one beaker of red solution and one beaker of water. Place a teaspoon of red solution from the first beaker into the second beaker. Then place a teaspoon of liquid from the second beaker into the first beaker. Is the amount of red solution in the first beaker equal to the amount of water in the second beaker?" The verbal presentation usually leads to a logical mistake. Recognizing that the word problem can be transformed into an algebraic representation leads readily to the correct solution.

THE PROBLEM

In education, words (verbal symbols) dominate instruction. If the symbolic representations used in instruction set boundaries within which students learn and remember concepts, this encoding specificity may place restrictions on students' abilities to translate the problem as given into a symbolic representation that admits to a solution. We believe that <u>encoding specificity</u>

characterizes students' knowledge especially when concepts are learned initially. Fuller understanding comes with repeated exposure to the material in different contexts and with repeated application of the concepts to different types of problems. With full understanding of the material, multiple symbolic representations of the same concept can be recognized and used to solve problems.

Partial understanding characterizes students' knowledge acquired from many courses.[1] We suspect that this partial understanding is dominated by the verbal and limited range of other symbolic representations used in classroom instruction. Moreover, we suspect that this understanding also depends on differences in how students symbolically represent information to themselves (aptitude). As a consequence, students' understanding of a subject will depend greatly on the symbolic representations used in instruction, their preferred symbolic mode of representing that subject, and the fit between instruction and aptitude.

If this characterization of students' understanding from instruction is roughly accurate, it has important implications for achievement measurement. Typical achievement-test items, in and of themselves, may require students to translate from the items' unique, predominantly verbal code to a more general (verbal or nonverbal) representation of the problem. Once the multiple-choice code has been broken, the student may also need to translate from this initial representation to some other symbolic form in order to solve the problem. If the purpose of achievement testing is to measure subject-matter knowledge, not verbal ability, typical objective tests may not this goal as well as they might. Rather, they may place irrelevant demands on certain test

[1]Instruction, especially with limitations in depth of coverage and time allocated to important concepts, is often incomplete. In addition, students' may hold misconceptions about the concepts to be studied that interfere with their understanding. Finally, their "mental effort" in acquiring the new concepts may be less than optimal.

takers, and thereby underestimate some students' subject-matter knowledge.

The purpose of this review is to bring diverse research to bear on our contention that current achievement tests may underestimate students' subject-matter knowledge and problem solving ability because of the mismatch between the symbolic form typical achievement tests use and the specificity of students' symbolic encoding that arises from instruction and individual differences. More specifically, we investigate the possibility that alternative representations of science problems affects achievement estimates for students varying in socioeconomic and ethnic/racial backgrounds. Science was chosen because of its importance in educational reform, and because alternative symbolic representations play a central role in "doing science."

REVIEW OF LITERATURE

To address the question of whether different symbolic representations produce different estimate of students' achievement, we first need to define what we mean by symbols and how different symbol systems might be identified and classified. This task is taken up first in the review. Next, we examine theory and research on (1) the effects of symbolic encoding on information processing and (2) the effects of translation among symbol systems on problem solving. We then place the issue of testing with alternative symbolic representations in the context of the literature on minority group testing.

Symbols and Symbol Systems

Definition. Gardner's distinction between symbols, symbol systems, and symbolic products helps clarify these concepts. A symbol is "any entity (material or abstract) that can denote or refer to any other entity. On this definition, words, pictures, diagrams, numbers, and a host of other entities are readily considered symbols" (Gardner, 1983, p. 301).

A symbol system is a set of symbols and rules for combining them. An additional required feature, according to Salomon (1979), is correspondence to a field of reference. The field of reference is important for giving meaning to the set of symbols and rules (see also Gross, 1974). As an example, Salomon describes the ambiguity of the meaning of red lights unless the field of reference is known: traffic lights, boats at sea, windows of alley apartments.

Finally, symbolic products consist of "all manner of symbolic entities that individuals create in order to convey a set of meanings, and that other individuals imbued in the culture are able to understand, interpret, appreciate, criticize, or transform" (Gardner, p. 301). Achievement tests, then, are symbolic products. This review addresses the adequacy of this particular symbolic product for its intended purpose, viz. estimating students' knowledge, skills, and problem solving abilities in a subject-matter domain.

Symbol System Classifications. Classifications of symbol systems vary from broad classes, such as Gross' (1974) five primary modes of symbolic behavior (linguistic, social-gestural, iconic, logico-mathematical, and musical), to more specific symbol systems, such as speech, print, drawings, diagrams, models, graphs, maps, numbers, geometry (Olson & Bruner, 1974) and pictures (Jay, 1973).

Only rarely have typologies of symbol systems been tied to instructional material. One of very few examples is Hooper's (1981) typology for mathematics: (1) equations--mathematical formalizations that represent precise relations between things; (2) graphs--simultaneous displays both of the general relationship between variables and the specific relationships between particular values of a set of variables; (3) tables--an intermediate representation between equations and graphs that provides information about the relations among values of a set of variables; (4) pictures--displays of specific instances, making the problem concrete, and (5) diagrams--visual displays of the general characteristics of a problem that demonstrate abstract concepts such as Venn diagrams, pie charts, flow charts. (We have applied Hooper's taxonomy to representations of science concepts, see Appendix.)

A second example is Lesh, Post, and Behr's (in press) taxonomy of representations systems found in mathematics. Lesh et al. distinguished five types of symbolic representations: (1) real scripts which organize knowledge around "real world events that serve as models for interpreting and solving other kinds of problem situations" (p. 6); (2) manipulative models (e.g., Cuisenaire rods) which contain elements that correspond to relationships and operations in many everyday situations; (3) pictures which, "like manipulative models, can be internalized as 'images'"; (4) spoken languages including special languages such as logic; and (5) written symbols, which in addition to written English, may involve specialized sentences such as x+3=6.

More frequently in educational research and curricula, symbol systems are cast in terms of media. Fitzgerald and Vance (1970), for example, give an extensive list of media that may be helpful for teaching mathematics: television, computers, programmed textbooks, computer assisted instruction, overhead projectors, audio tapes, film loops, film, radio, academic games, and manipulative devices (e.g., geoboards).

These media are not single symbol systems, however, but are combinations of them. Film, for example, uses many symbol systems, including photography, gesture, speech, dance, music, and film-specific symbol systems (Salomon, 1979).

Even the specific symbol systems mentioned above may not be single or pure symbol systems. Diagrams, for example, may not be a single symbol system, but may be a cluster of distinct symbol systems. Schematic drawings of electric wiring, pie charts, flow charts, and Venn diagrams can all be considered diagrams but they use somewhat different symbols (circles, squares, numbers, arrows) and even the symbols that they have in common may have different meanings (compare a circle in a flow chart with a circle in a pie chart). As is discussed next, the literature on symbol systems gives little guidance on deciding how to distinguish one symbol system from another.

Dimensions of Symbol Systems. To define a taxonomy of symbol systems that is relevant to a particular knowledge domain, it is necessary to clarify the critical dimensions that distinguish symbol systems from each other. The dimensions that have been proposed to differentiate symbol systems include resemblance (Goodman, 1968; Eisner, 1970; Sowell, 1974) and notationality (Salomon, 1979).

By resemblance, we mean the extent to which symbols resemble their referents. At one extreme are symbol systems that resemble or imitate their referents (iconic), for example, replica models. At the other extreme are symbol systems that do not resemble their referents (analogue), for example, verbal and numerical systems. Salomon (1979) speaks of description vs. depiction, respectively (see also Chapanis, 1961). Sowell (1974) classifies symbol systems into categories of concrete, pictorial, and abstract, and Eisner (1970) classifies symbols as representational (realistic depictions), conventional where symbols stand for ideas or events in a particular culture (e.g., Valentine's heart), connotative where symbols result from distortions of conventional symbols (e.g., Picasso's animals), and qualitative where symbols represent some idea or feeling.

Goodman (1968) and Salomon (1979) argue that resemblance is an unsatisfactory way of defining symbol systems because resemblance is ambiguous; symbols can resemble their referents in many ways. They argue instead that what really distinguishes between depiction and description is notationality. Symbol systems can be notational or nonnotational or somewhere between these two extremes (Salomon, 1979). In notational systems, the symbols are discrete and discontinuous and there is a one-to-one correspondence between symbols and their referents. For example, each note on a musical score corresponds to a musical pitch. In nonnotational systems, symbols are not disjoint but are continuous, and each element does not correspond to one and only one referent (Gardner, Howard, & Perkins, 1974). For example, pictures are nonnotational because each element could represent many things (a line in a painting can represent a contour or fold or depth), and the picture could lead to multiple meanings (Salomon, 1979, p. 33). As an intermediate case, Salomon argues that language is only partly notational because the elements are often ambiguous.

These dimensions are of little help in deciding how to distinguish between symbol systems. Salomon (1979, p. 35) admits that notationality is only one of many possible ways to distinguish among symbol systems. Furthermore, the concept of notationality is too abstract to help define taxonomies of symbol systems for particular knowledge domains. Clearly, then, while the literature presents examples of symbol systems, no one has clarified the critical dimensions that distinguish them, and we do not intend to attempt to do so either. Rather, this review leads us to the conclusion that we need to develop a symbol system taxonomy that is heuristic for our specific purposes.

Encoding Specificity

Proposition vs. Multi-Representation Controversy. An age old controversy continues about how information is encoded internally. One view is the propositionalist position: that all information is encoded in a single underlying form of mental representation called propositions (Anderson & Bower, 1973; Chase & Clark, 1972; Pylyshyn, 1973, 1976; Reed, 1974; Palmer, 1975; Norman & Rumelhart, 1975; Olson & Bialystok, 1983). Propositions are abstract and do not correspond directly to words or pictures or any other symbolic mode. Pictorial information, for example, is "alleged to be processed sequentially and complexly and in a way that is modality-independent. Each stimulus needs to be decomposed into higher-level then lower-level propositions until reduced to primitive propositions about points, angles, and numerous other dimensions" (Salomon, 1979, p. 67).

The competing view of encoding posits that information is encoded in terms of properties that are modality specific. Most of the proponents of this view are concerned with the processing of pictorial information and maintain that images are encoded in different mental representations from, say, verbal information (Shepard, 1978; Brooks, 1967; Kosslyn, 1975; Kosslyn & Pomerantz, 1977; Paivio, 1971, 1976; Bower, 1972).

Although the propositionalists and the multi-representationalists disagree about the deepest level of mental representation (proposition vs. modality-specific representation), both sides agree that, at a higher level, there exist different kinds of mental representations or mental models. No one seems to deny that there is a phenomenon called mental imagery (Anderson, 1978, p. 251, emphasis in original); the controversy centers on the deepest level of the internal representation. Even propositionalists agree that a learner may have distinct mental representations of pictures and words at some level above the propositions. An extreme case is Johnson-Laird (1983) who, even though a propositionalist, hypothesizes the existence of six types of physical mental models (corresponding to the physical world) and four types of conceptual mental models (corresponding to abstract concepts).

We are concerned with the level of encoding that admits multiple mental representations, not the most basic level of encoding, so the controversy is not relevant to our project. We base our project only on the assumption that, at some level, information that is presented in different symbolic modes is encoded in different mental representations ("encoding specificity"). On that point cognitive psychologists are in agreement.

Tulving's Encoding Specificity Principle. The notion of symbolic encoding specificity should not be confused with

Tulving's Encoding Specificity Principle. In their encoding specificity principle, Tulving and Thomas (1973, p. 353) hypothesized that information is encoded according to the context and requirements of the task: "What is stored is determined by what is perceived and how it is encoded, and what is stored determines what retrieval cues are effective in providing access to what is stored." They illustrated their principle with homographs: words that have different meanings; for example, if the word "violet" is encoded as a color name, it normally will not be retrieved as a type of flower or girl's name. Although there is a common element between Tulving's principle and our hypothesis about symbolic encoding specificity, that features of the learning task influence encoding, Tulving was not concerned with the symbolic representation of the learning material.

Evidence for Symbolic Encoding Specificity. We cannot find research directly related to symbolic encoding specificity. The closest evidence is indirect and comes from studies finding that people acquire different knowledge from different media. The results of Thorndyke and Hayes-Roth's (1982) map-learning study, for example, support their hypothesis that when learning from a map, people encode global spatial relations, images that can be scanned and measured like a physical map; whereas when learning through navigation, people acquire knowledge about the routes connecting different locations.

The Need for Research. The symbolic encoding specificity hypothesis as applied to multiple symbol systems--that material presented in different symbolic forms will be encoded differently--has enormous implications for instruction, but the link has not been made. Presenting information to students in multiple symbol systems, say, pictures and numbers, requires not only understanding of the material in each symbol system, but requires an extra step of translation to connect the two. The studies comparing the effectiveness of combinations of symbol systems (e.g., pictures and words) to single symbol systems (e.g., words) do not take this step into account in hypotheses about how information is processed nor in their interpretation of results. As only a few researchers have recognized (Wiebe, 1983; Sowell, 1974), this extra step may make it more difficult, not easier, to learn from multiple representations.

Translation among Symbol Systems

Consider Charlie, a student who has just learned to determine the area of a rectangle and is then given a picture of a (rectangular or square) living room and asked to determine how large a rug would be needed to fit it wall to wall. The student is fully capable of determining the area of a rectangle (area = length times width); and has first hand experience of rugs in living rooms. Yet he may not see that his geometric knowledge can be applied directly to the problem at hand. To make this link requires that he translate between one symbol system (geometry) and others (verbal and iconic). And yet, Charlie may be symbol system bound. If he is not given two of the triple--area, length, width--in a computational problem or a schematic of a rectangle, he may not link his geometric knowledge to the problem at hand. Once the translation is made, however, the problem becomes trivial.

Amy, a fifth grade student in the high math group, was confronted with a problem that went something like this: Given two workers moving furniture into a house, determine the minimum time needed to complete the job when each task required a specified amount of time, some tasks required the two movers to work together, and some tasks had to be done before others. The problem was solved when it was recognized that a piece of paper could be used to stand for each task, and that the length of the paper could be used to denote the time required to complete the task. By placing the pieces of paper above a time line and moving them around, the minimum time required to complete the job (under the constraints given) could readily be determined. With this problem, Amy might have recognized, given time and motivation, that some other symbolic representation, such as algebra, might also have yielded a solution to the problem. Nevertheless, by translating from the word problem to the spatio-temporal symbol system, the problem became tractable and the solution straightforward. That is, the rules for manipulating the spatio-temporal symbols, including moving the rectangles around to meet a set of criteria, provided the operations needed to move from the problem's givens and constraints to its solution.

These are but two examples among many where the requisite knowledge and experience of the problem solver are more than adequate to solve a problem, but the symbolic form of the problem as given (here predominantly verbal) does not admit to a ready solution. The "real" problem for the problem-solver is to recognize that the same problem can be represented by another symbol system, one in which the problem can be solved.

Tentative Definition of Symbol System Translation. These two examples convey, informally, what we mean by translation from one symbol system to another. Heuristically, we define translation from one symbol system to another as the process of mapping the information contained in one or more symbolic forms (e.g., geometry) into one or more, other symbolic forms (e.g., verbal/pictorial). Two prerequisites for translation are relevant: (a) adequate domain knowledge (declarative and procedural), and (b) experience.

We do not assume a one-to-one mapping of symbols in one system onto the symbols in another system. The mapping syntax, for example, includes transformations such as combining verbal and numeric symbols (task and time in Amy's problem) into a primarily spatio-temporal representation (pieces of paper of varying lengths).

We also do not assume that only one mapping from a given symbolic representation to another exists for problem solution. Individual differences will play a role as will the context of the problem solving situation. That is, individual differences in "mentally" representing information symbolically and manipulating it will influence the translation process. Hence, students may arrive at a problem solution along different symbolic paths.

Research on Translation. Lesh (in press) defined "translation among representations" in mathematics as a problem-solving process of: (1) translating from the 'given situation' to a mathematical model, (2) transforming the model so that desired results are apparent, and (3) translating the model based result back to the original problem situation to see if it is helpful and makes sense" (p. 1). Lesh, Post, and Behr (in press, p. 8) identify five steps in the translation process, corresponding to modeling a mathematical problem: (1) simplifying the problem by ignoring irrelevant information, (2) mapping between the givens and the "model," (3) transforming the properties of the model to arrive at a result, (4) translating the result back to the givens, and (5) evaluating the fit of the result to the givens.

Lesh uses the following problem to exemplify this definition (Lesh, in press, pp. 1; see also Lesh et al., in press):

> Al has an after-school job. He earns $6 per hour if he works 15 hours per week. If he works more than 15 hours, he gets paid "time and a half" for overtime. How many hours must Al work to earn $135 during one week?

After paraphrasing the problem and mulling it over, the student might arrive at a mathematical statement such as:

$$(6 * 15) + 9(x-15) = 135$$

At this point, the student solves for x by applying a series of algebraic transformations to the statement:

$$x = \frac{135 - (6 * 15)}{9} + 15$$

This arithmetic sentence can then be solved using arithmetic transformations: x = 20; Al would have to work 20 hours. Beyond the initial mulling over process, the solution, according to Lesh, involves three significant translations: one from English sentences to an algebraic sentence, another from algebra to arithmetic, and a final translation from arithmetic back to the original problem.

Lesh (in press, p. 2) provides another example in which the same problem can be translated into more than one symbolic representation--algebraic or geometric--that admits to problem solution..

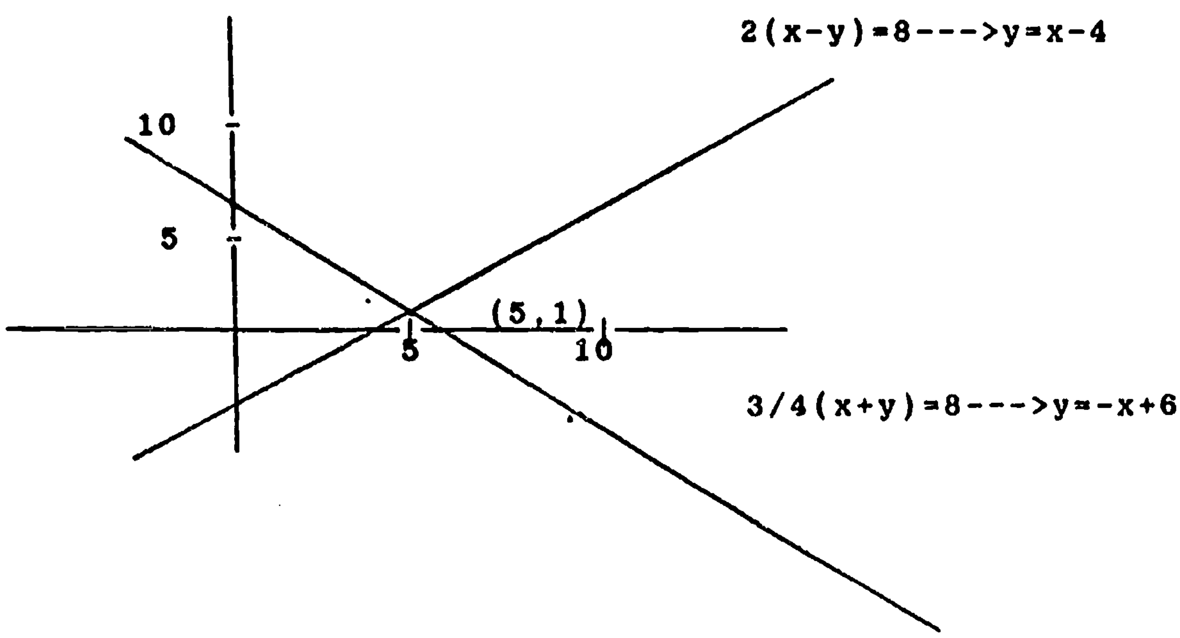
> A boat, traveling upstream on a river, takes two hours to reach its destination eight miles away. The return trip downstream takes one hour and twenty minutes. What is the speed of the river current?

The student might solve the problem using two unknowns: x = speed of boat; y = speed of current. Two algebraic sentences can be used to model the problem:

$$2(x,-y)=8 \text{ and } 4/3(x+y)=8.$$

The solution, x = 5 and y = 1, can be readily attained.

Alternatively, the algebraic model can be translated into a geometric model by graphing each of the two equations. The values that satisfy both equations will be the coordinates of that point common to both graphs:



Finally, note that if the student continues solving algebraically for x and y in the two equations, there is a corresponding graphical representation. For example,

$$x - 4 = x + 6$$

$$2x = 10,$$

produces one graph with a horizontal line at y = 10 (y is a constant), and a second graph in which 2x produces a line passing through 0,0 ... 5,10. Although this would be a tedious process with pencil and paper, a computer can produce a graph corresponding to the algebraic solution steps instantaneously for the student. When this happens, Lesh (in press, p. 2) notes that:

> [M]any students ... have noticed that, for any given problem, intersection points for the pairs of lines at each solution step always lie on a single vertical line, which turns out to be at the solution point for x. Some ... think about and describe why this invariant feature occurs. So ... students ... generate significant new questions, and ... [use] informal language to describe rather deep principles related to: (1) invariance under mappings among isomorphic systems, and (2) invariance under transformations within a given system.

In a study comparing two groups ($n_1 = n_2 = 10$) of ninth graders studying comparable sequences of instruction on simultaneous linear equations, both groups received exactly the same examples, exercises, problems and applications. The groups differed in the order the various items were given, the part of the activity that was done by computer (rather than by the student), and the extent to which the graphs of solution steps were plotted. The "utilities" group used the computer as a tool, performing computations and assisting in problem solving and translating between equations and graphs. The "computation" group was guided by the computer through the steps needed to compute solutions to pairs of linear equations. "In a sense, the students in the 'computation' group performed the exact role that ... [the computer] had performed for the 'utilities' group, and the computer performed the role that the 'utilities' group students had performed" (p. 7). The "utilities" group outperformed the "computation" group on applications problems. They also outperformed "their originally comparable peers on the computation half of the test.... Some of the most impressive observations [from interviews] that the students in the 'utilities' group made had to do with the kinds of 'invariance under translations and transformations' facts that were described [above]. No similar observations were made by anyone in the 'computation' group" (p. 7).

Based on this and earlier work (Behr, Lesh, Post and Wachsmuth, 1985; Post, 1986), Lesh argues that "the ability to do these translations are significant factors influencing both mathematical learning and problem-solving performance" (Lesh et al., in press, p. 7). Indeed, students able to solve mathematics problems do so by representing the problems not in a single symbol system, but in several systems, each corresponding to different parts of a word problem (Lesh, Landau, and Hamilton, 1984).

Most students, however, not only have difficulty understanding word problems and pencil and paper computations,they lack an understanding about models and languages needed to represent and manipulate ideas in problems (Behr et al., 1985; Post, 1986). To diagnose these difficulties, Lesh et al. (in press, p. 8) recommend presenting an "idea in one representational mode and asking the student to render the same idea in another mode. Then, if the diagnostic questions indicate unusual difficulties with one of the [symbolic representations] ... other [representations] ... can be used to strengthen or bypass it.

Herein lies the kernel of our idea about achievement testing. Achievement tests present problems in one dominant symbolic form: verbal, multiple-choice (often word) problems. Not all students have experience with such representations, especially if other representations have been taught with greater frequency, or if this representation has not been taught specifically. Hence, switching from the usual verbal multiple-choice word problem to other representations might reveal knowledge that otherwise would be judged absent.

In addition to research on mathematical translation there are two related psychological literatures that provide important background for our work on translation. The literature on transfer is one, and the literature on insight is the other. Both are voluminous; we do not intend to review them comprehensively. Rather, we take a representative study of each and show how it does and does not relate to our notion of translation.

Transfer. Transfer may be defined as "the extent to which the learning of an instructional event contributes to or detracts from subsequent problem solving or the learning of subsequent instructional events" (Royer, 1979, p. 53). A wide variety of types of transfer have been identified, e.g., "vertical," "lateral," "specific," "nonspecific," "near," "far." Both lateral and far transfer come closest to what we mean by translation.

Lateral transfer is "a kind of generalization that spreads over a broad set of situations at roughly the same level of complexity" (Gagne, 1965, p. 231). For example, lateral transfer occurs when a child realizes that her knowledge of fractions is relevant to dividing up a prized, jointly owned, marble collection. Far transfer arises when an individual recognizes that the organization of the stimulus complex in memory maps onto a differently organized stimulus complex presented by a task. For example, far transfer occurs when the student realizes that two-column addition applies to the solution of a word problem, or more generally, when an individual realizes that school learning applies to real-world problem situations (as in the geometry/rug example above.)

The definitions of lateral and far transfer seem to fit situations we have described as requiring symbol system translation, but are considerably broader. The little research that has investigated these types of transfer has focused on content or knowledge structures, however, and not on symbol systems.

DiVesta and Peverly (1984), for example, manipulated the context in which novel information was learned to examine the effect of context on transfer. For instance, a concept was taught in one context, that of antique dealers. Far transfer, then, was defined as recognizing instances of a concept in a new context (e.g., magic shows). DiVesta and Peverly (1984) hypothesized and found that "learners will acquire limited knowledge of a concept if they practice (encode) on examples appropriate to only the single context specified in the rules.... [Practice] on examples from a variety of contexts (encoding variability) will result in decontextualization due to the availability of multiple retrieval paths" (p. 109; see also Baddeley, 1982; Kerr, 1982; and Smith, 1982).

Suppose that, instead of varying the content of the contexts such as "antique dealers," and "magic shows," we varied the symbolic representation of the examples during practice. In this case, we would have one group apply the concept to verbal (same) exemplars (without the context tag), another group apply the concept to iconic (different) exemplars, and a third practice on a mixture of the two. We would, then, have an experiment that tested some aspects of our notion of symbol system translation.

Insight. Insight refers to "the process by which the meaning, significance, pattern, or use of an object or situation becomes clear; or the understanding thus gained. In Gestalt theory, insight was originally described as happening suddenly, and as a novel reaction not based on previous experience" (English and English, 1966, p. 264). Sternberg (1984, p. 277) claims that three processes underlie insight: selective encoding, selective combination, and selective comparison. Selective encoding "involves recognizing those elements of a problem that are relevant for task solution, and those elements that are not" (p. 277). Selective combination "involves figuring out how to combine information that has been selectively encoded" (p. 277). And, most germane to translation, selective comparison "involves figuring out how new information can be related to old information" (p. 277). Sternberg's example of selective comparison reveals symbol system translation:

> Kekule's discovery of the structure of the benzene ring hinged upon his recognition that a dream he had of a snake reaching back and biting its tail provided the basis for the geometric structure of the ring [p. 277].

Sternberg and Davidson (cited by Sternberg, 1984) demonstrated that the three insight processes were additive by manipulating the amount and kind of cuing subjects received before attempting to solve problems like:

> Water lilies double in area every 24 hours. At the beginning of the summer there is one water lily on a lake. It takes 60 days for the lake to be come covered with water lilies. On what day is the lake half covered?

The problem can be solved by recognizing that the problem can be translated to some form of numerical representation. For example, if each day (24 hours) the area doubles, then from day 59 to day 60, the lilies will double to fill the lake; on day 59 the lake must have been half full.

Conclusion. The construct, symbol system translation, focuses attention on the roles of: (a) prior knowledge and experience, (b) the learning context that produces specific symbolic encoding of new knowledge, (c) the symbolic demands of the problem solving context, (d) the processes that map knowledge learned in one or more symbolic forms onto another symbolic representation that includes cognitive operations needed for problem solution, and (e) individual differences in problem-solvers' symbolic encoding aptitudes. The construct appears to offer promise both in focusing theory and research on a process that has not been directly researched to date, and in explaining, at least in part, why individuals have difficulty solving novel problems.

Symbolic Representation and Minority Group Testing

We suspect that some students and some groups of students may better process information, and hence be tested more accurately, in primarily nonverbal rather than verbal symbolic forms. Candidate groups of students who may be disadvantaged when tested in verbal form are minority students or students from non-majority cultural or language backgrounds. This supposition follows from Gardner's (1983) notion of symbolic products (such as achievement tests) as consisting of symbolic entities comprehended by individuals in a particular culture. Yet, the research on minority group testing rarely touches on the possibility of alternative symbolic forms of tests or test items. Rather, the literature on minority group testing has focused on (1) the validity of group differences in test scores (test bias), (2) the testing of linguistic minorities, and (3) the development of culture-fair tests. We address each topic in turn.

Test Bias. A huge literature has developed out of the recognition that group differences on intelligence and achievement test scores exist. Much of the research has tried to determine the accuracy (validity) of differences in test scores across ethnic/racial groups (Cole, 1981). When a test yields group differences that are inaccurate, the test is considered biased.

At least three types of bias have been identified. The concern here is whether test predict eventual criterion performance equally well for different groups (American College Testing Program, 1973; Campbell, Crooks, Mahoney, & Rock, 1973; Jensen, 1980; Kallingal, 1971; Kirkpatrick, Ewen, Bennet, & Katzell, 198; Linn, 1975; Linn & Werts, 1971; McNemer, 1975; Stanley, 1971; Stanley & Porter, 1967; Temp, 1971). If groups show differences in predictor test scores, the question is whether the predicted differences in criterion scores are accurate (Cole, 1981). A second type of bias concerns the internal test structure. If the relationships within a test differ across groups of examinees, the test might be considered biased (Humphreys & Taber, 1973; Jensen, 1980).

The final type of bias concerns the item. Items that distinguish between groups may not mean the same thing for different groups (Cole & Nitko, 1981; Rudner, Getson, & Knight, 1980). Even when group differences in item responses have been found, however, they have rarely been interpretable. One exception is Scheuneman's (1979) findings that items worded negatively and items with unfamiliar formats on a school ability test showed bias against young black students (see Cole, 1981). Although Scheuneman's results suggest that features of an item may disadvantage some groups, that study focused on variations of verbal items, not alternative symbolic forms.

In summary, although a large number of statistical techniques have been developed to detect test bias and to determine the appropriate statistical corrections in test scores to ensure fair selection of individuals from different cultural groups, the work in test bias has rarely investigated the mechanisms causing differences between groups nor has it investigated how to design tests that maximize the performance of all groups.

Testing of Linguistic Minorities. One area of minority group testing does focus on the sources of difference between groups: in particular, the language background of the examinee. Psychologists have long known that standard English tests may not accurately reflect the abilities of achievement of students whose native language is not English or who are not fluent in English. Olmedo (1981, p.1083) raises the question about whether any test "can be used to infer constructs that are conceptually equivalent across diverse cultural and linguistic groups." In operationalizing the issues surrounding testing of linguistic minorities, Olmedo and others are concerned mainly with the language of the test, the difficulty with developing equivalent versions of tests of different languages, and the need to match the language and cultural background of the examiner and examinee.

The issues in testing of linguistic minorities, then focus on the language of testing, rather than the symbolic form of the test. The concern is whether the words should be in English or Spanish or nonstandard English (e.g., the Black Intelligence Test of Cultural Homogeneity or BITCH Test), not whether the problem should be presented primarily in words or primarily in some other symbolic form.

Cross-Cultural Testing. The only area of testing that addresses the symbolic form of the test is the development of culture-fair tests. The developers of cross-cultural tests have tried to eliminate factors that distinguish between cultures, including language, reading, speed, and test content (Anastasi, 1982). Culture-fair tests, then attempt to minimize language or reading requirements, are not speeded, and try to avoid using information that may be specific to particular cultures. Typical culture-fair tests are nonverbal and are figural or pictorial (e.g., Leiter International Performance Scale, Culture Fair Intelligence Test, Raven's Progressive Matrices, the Goodenoough-Harris Drawing Test). As Anastasi and others have pointed out, however, even nonverbal tests may be heavily culturally loaded (Anastasi, 1961; Irvine, 1969; Jensen, 1968; Ortar, 1963; Vernon, 1969). Pictures and other nonverbal symbols mean different things to people from different cultures (Miller, 1973; Segall, Campbell, & Herskovitz, 1966).

The attempt to eliminate cultural factors from a test--to develop the lowest common denominator--is to move away from being able to identify what an examinee knows or can do. Because "each culture and subculture encourages and fosters certain abilities nd ways of behaving; and it discourages or suppresses others" (Anastasi, 1982, p. 344), it is important to develop tests that capitalize on the strengths of students from different cultural backgrounds so that an accurate measure of ability can be obtained. Culture-fair tests do not do this.

Conclusion. Although the research on minority group testing recognizes that standard verbal tests (usually in English) may disadvantage students from non-majority cultural and language backgrounds, there has been little attempt to determine the strengths of particular cultural and language groups nor to develop tests that capitalize on them. Most alternatives tests are verbal, just translated into another language. The few nonverbal tests that have been developed try to eliminate cultural advantages rather than taking advantage of them.

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APPENDIX

DEVELOPMENT OF TAXONOMY USED IN SCIENCE TEXTBOOKS: CONCEPTS OF HEAT AND TEMPERATURE

This study is part of a project aimed at improving the measurement of problem solving skills in achievement testing. We suspect that estimates of achievement from traditional multiple-choice tests may underestimate students' achievement because students, when short of full understanding, may be bound by the symbol system in which they learned the material, or by the way they remember the material. The purpose of this study was to develop a rough taxonomy of symbolic representations of physical science concepts used in high school textbooks.

The Problem

If achievement tests are intended to measure students' subject-matter understanding, not verbal ability, many of these tests may miss their goal. Typically achievement tests present problems in a unique, verbal form with a stem and multiple alternatives. Yet if the student learned (encoded) the concepts using a different representation, the student must "translate" to a new representation before being able to answer the question. What may be needed is an achievement test that offers multiple symbolic representations of the same content domain to ascertain the dependency of student achievement estimates in symbolic representations. A first step in this research is to characterize how physical science concepts are represented in instruction. This taxonomy of representations, then, might guide the construction of achievement test items in alternative symbolic forms.

A review of literature on symbol systems (Shavelson, Webb, and Lehman, this report) showed that the dimensions of symbolic representations identified in research are too abstract to guide the development of a testing instrument. Only rarely have typologies of symbol systems been tied to instructional material. Hooper (1981) is an exception. She developed a taxonomy of symbolic representations for mathematics which included these categories: equations, graphs, tables, pictures, and diagrams. Hooper's categories served as a starting point in this study for developing a taxonomy of symbol systems used to teach a set of science concepts. This category system was applied to the concepts of heat and temperature in three textbooks widely used in the Los Angeles Unified School District (LAUSD). Although students receive information from a variety of sources (e.g., teacher, textbook, other students, reference materials, class demonstrations) we chose to examine popular textbooks because of their wide application and science teachers' dependency on them. Moreover, because of the difficulty in defining a general taxonomy relevant across all areas of science, we focused on heat and temperature. This topic is covered in nearly all science curricula at the secondary level, is not extremely difficult to learn, admits to multiple symbolic representations of its concepts, and has been the focus of research on misconceptions held by students.

Method

Textbooks. Three textbooks, Physical Science (Scott, Foresman, 1986), General Science (Allyn & Bacon, 1985), and Focus of Physical Science (Merrill, 1986), were chosen for the study because they are used throughout the LAUSD in the high school physical science course, Modern Science. This course is targeted at students of average to below average abilities who most likely will not attend college.

Procedures. The first step in developing a taxonomy was to apply Hooper's work to the symbolic representations of heat and temperature concepts used in the textbooks, and then to modify this taxonomy, as needed. The next step was to use the modified taxonomy, determine the frequency with which each type of symbolic representation was used for each key concept.

All examples of symbolic representations of key concepts in heat and temperature were extracted from each of the textbooks. (Verbal representations were not included in this exercise, but were understood to be a major symbolic representation of science concepts in textbooks.) Sixty-eight examples of alternative symbolic representations were found. Three raters then independently sorted the examples into categories of distinct symbolic representations. Although Hooper's labels were used as a starting point to name the categories, the raters were encouraged to modify the categories as needed. The raters then compared their results, discussed discrepancies, and came to a consensus on categories of symbolic representation used for heat and temperature in the three textbooks.

This taxonomy was then applied to the presentation of a set of specific concepts within heat and temperature to determine which symbol systems were used for each concept. The following eight topics were the focus of this investigation: (1) definitions of heat and temperature, (2) thermometers and temperature scales, (3) specific heat, (4) heat transfer, (5) pressure, (6) molecules and movement, (7) heating systems, and (8) insulation. A tally was made of the frequency with which each symbol system was used to represent each concept.

Results

A Taxonomy. Six basic classifications of symbolic representations, similar to Hooper's were identified: verbal, diagrams, photographs, tables, graphs, and equations. However, the raters divided two of these classifications--diagrams, and equations--into finer categories based on distinctive characteristics.

Diagrams were defined along three dimensions: concrete vs. abstract; static vs. dynamic; and labeled vs. unlabeled. Although only four types of diagrams were found in the texts, all possible combinations of these dimensions produce eight distinct types of diagrams (see Figure 1). Equations were further defined as being expressed in either words or symbols (see Figure 2).

Insert Figure 1

Insert Figure 2

The only tables found in the three textbooks contained lists of words and numbers (see Figure 3). Nevertheless, the raters identified a second possible type of table, a contingency table.

Insert Figure 3

Ten distinct types of symbolic representations, then, were found in the textbooks: (1) Verbal; (2) Diagrams that are concrete, show movement and have labels (n=10); (3) Diagrams that are concrete, do not show movement, and have labels (n=9); (4) Diagrams that are concrete, show movement, and are unlabeled (n=4); (5) Diagrams that are abstract, show movement, and are unlabeled (n=2); (6) Photographs (n=33); (7) Tables (n=6); (8) Equations with words (n=1); (9) Equations with symbols (n=1); and (10) Graphs (n=2).

However, the full taxonomy includes some categories for which examples could not be found. In all, the taxonomy contains fifteen distinct symbolic representations:

(1) verbal
(2) diagram - concrete/static/labeled
(3) diagram - concrete/static/unlabeled
(4) diagram - concrete/dynamic/labeled
(5) diagram - concrete/dynamic/unlabeled
(6) diagram - abstract/static/labeled
(7) diagram - abstract/static/unlabeled
(8) diagram - abstract/dynamic/labeled;
(9) diagram - abstract/dynamic/unlabeled
(10) equation - words

(11) equation - symbols

(12) table - contingency

(13) table - list

(14) graph

(15) photograph.

<u>Frequency of Symbolic Representations</u>. Table 1 shows the symbol representations found in each text for each key concept.

Insert Table 1

The verbal representations are counted in number of paragraphs while all other symbol systems are counts of individual representations. Table 2 provides a summary of the frequency of each symbol system across all key concepts and textbooks.

Insert Table 2

Another way of characterizing the heavy verbal presentation in the texts is to consider that all eight key concepts were represented verbally. The next most frequently used symbolic representation was photographs, most of which were more cosmetic than substantive. Diagrams classified as concrete/static/labeled were used to represent three of the concepts. Diagrams--concrete/dynamic/labeled and diagrams--abstract/dynamic/unlabeled appeared for two concepts each. The remaining four symbolic representations, diagrams--concrete/dynamic/unlabeled, tables in list form, equations with words, and equations with symbols, each occurred for one key concept.

Conclusions

Although taxonomies of symbol systems used to represent science concepts were not found in the science-education research literature, this study demonstrates that it is possible to define such a taxonomy. It is a lengthy process and most likely needs to be tied directly to specific concepts of interest. It is obviously difficult to quantify our findings. However it is clear that the textbooks relied almost entirely on verbal exposition.

FIGURE 1: FOUR TYPES OF DIAGRAMS

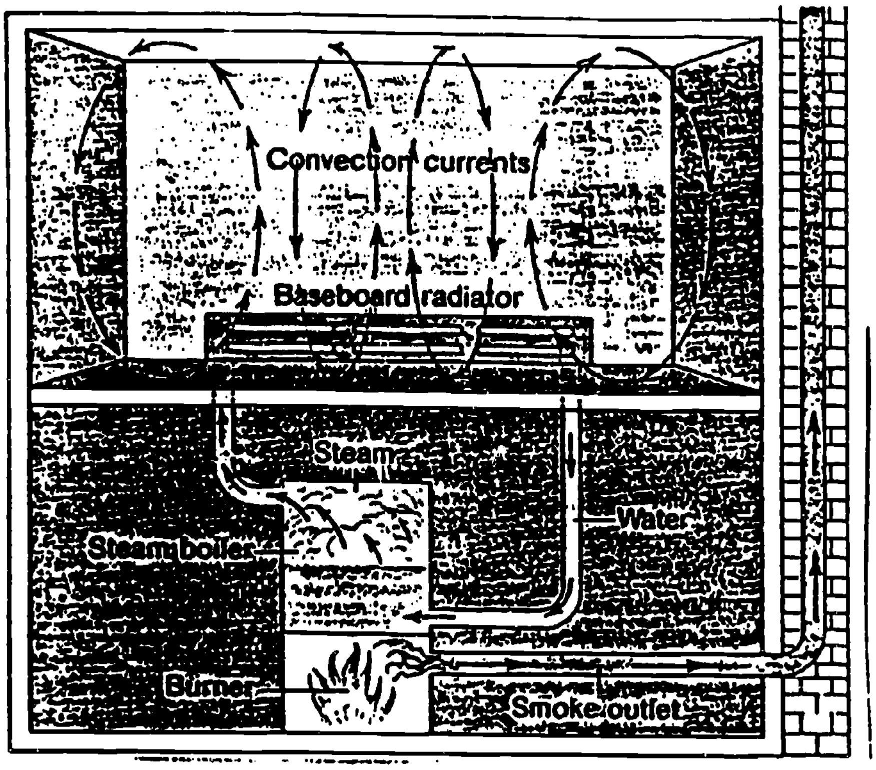


Figure 15-11. In a steam heating system liquid water absorbs the heat needed to vaporize it. When the vapor condenses back to a liquid in the radiator, what happens to this heat of vaporization?

The heat is set free into the room.

(A) Diagram - Concrete/Dynamic/Labeled

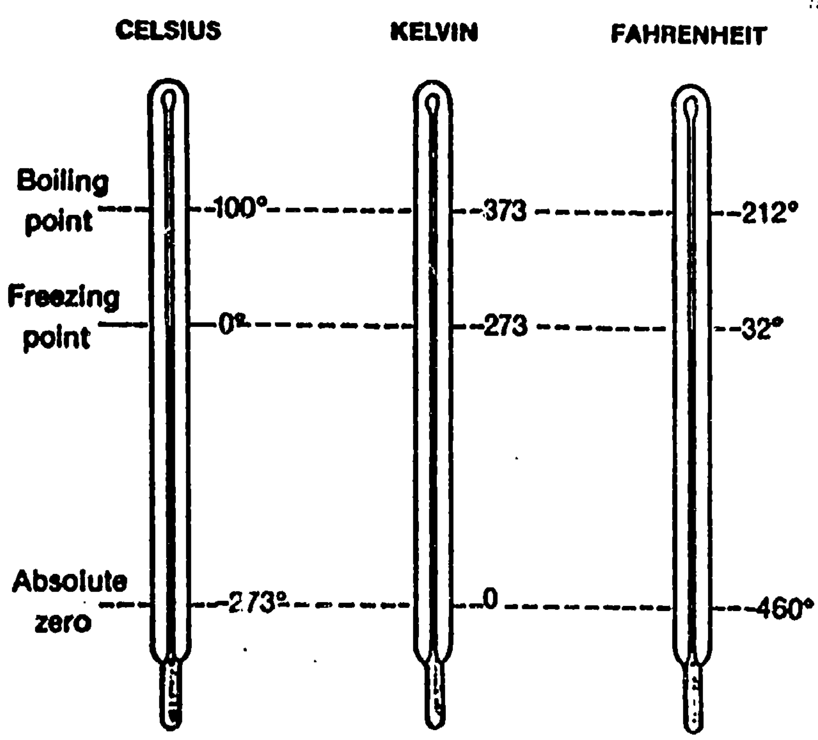


Figure 15-6. Temperature is measured on any of three scales: Celsius, Kelvin, and Fahrenheit. Which two are based on the boiling and freezing points of water?

Celsius and Fahrenheit

(B) Diagram - Concrete/Static/Labeled

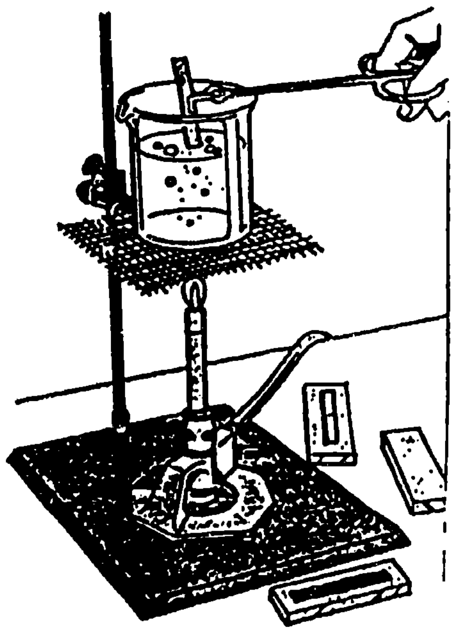
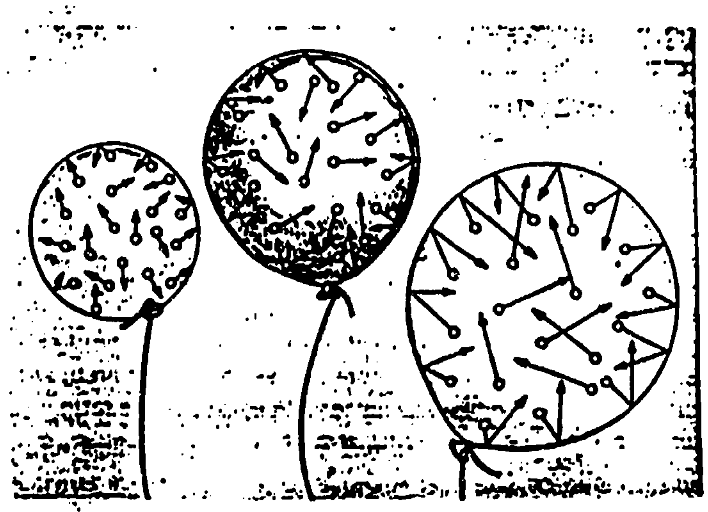


FIGURE 19–2.

(C) Diagram - Concrete/Dynamic/Unlabeled

Figure 18-5 When air inside a balloon warms, the air particles move faster and with more force. The pressure on the inside surface increases and the balloon expands.



(D) Diagram - Abstract/Dynamic/Unlabeled

FIGURE 2: TWO TYPES OF EQUATIONS

Heat absorbed or released = *Change in temperature* × *Mass* × *Specific heat capacity*

$$H = \Delta t \times m \times C_p$$

Δ means change, so Δt means change in temperature.
Δt equals $t_2 - t_1$ when heat is gained. When heat lost Δt equals $t_1 - t_2$.

$$P = \frac{F}{A}$$

(A) Equations with Words

(B) Equations with Symbols

FIGURE 3: TABLE IN LIST FORM

Table 18-1: Specific Heats of Various Substances

Substance	Specific heat (J/g/°C)	Substance	Specific heat (J/g/°C)
aluminum	0.92	iron	0.46
brass	0.38	lead	0.13
copper	0.39	olive oil	2.0
glass	0.84	silver	0.24
glycol	2.6	water	4.2
gold	0.13	zinc	0.38
ice (0°C to −20°C)	2.1		

TABLE 1: FREQUENCY OF SYMBOL SYSTEMS BY KEY CONCEPTS WITHIN EACH TEXTBOOK

	CONCEPTS							
Symbol System	1	2	3	4	5	6	7	8
V	A 3 B 4 C 7	A 4 C 8	A 6 B 2 C 1	A 4 B 2 C 2	C 1	A 6 B 6 C 5	A 6 B 5	A 8 B 9 C 8
DADU				A 1	C 1			
DCDL						A 1		A 3 B 2 C 2
DCDU								B 1
DCSL		A 2 C 1					B 2	C 1
TL			A 1 B 1 C 1					
EW				A 1				
ES				A 1				
P		B 2 C 1		A 2 B 2		A 4 B 1 C 2	A 1 B 1	A 1 B 2 C 1

Textbooks are labeled A, B, and C.
Concepts are: 1. Definitions of heat and temperature; 2. Thermometers and temperature scales; 3. Specific heat; 4. Heat transfer; 5. Pressure; 6. Molecules and movement; 7. Heating systems; 8. Insulation
Symbol Systems are: V - Verbal; DADU - Diagram/Abstract/Dynamic/Unlabeled; DCDL - Diagram/Concrete/Dynamic/Labeled; DCDU - Diagram/Concrete/Dynamic/Unlabeled; DCSL - Diagram/Concrete/Static/Labeled; TL - Table in List Form; EW - Equation with Words; ES - Equation with Symbols; P - Photograph

TABLE 2: FREQUENCIES OF SYMBOL SYSTEMS FOR ALL KEY CONCEPTS

SYMBOL SYSTEM	FREQUENCY
Verbal	97 paragraphs
Diagram - Concrete/Static/Labeled	4 diagrams
Diagram - Concrete/Dynamic/Labeled	4 diagrams
Diagram - Concrete/Dynamic/Unlabeled	1 diagram
Diagram - Abstract/Dynamic/Unlabeled	2 diagrams
Equation - Words	1 equation
Equation - Symbols	1 equation
Table - List	3 tables
Photograph	12 photographs