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ABSTRACT

The mental representations used by experts and novices for organizing their knowledge of a discipline have been studied by observing the categorization schemes these subjects produce when presented with a diverse group of problems. In this study, seven biology faculty, eight certified genetic counselors, and 26 students were asked to organize a set of 28 genetics problems based on how the person would solve them and to describe their schemes in writing. Subjects were categorized according to their success on four moderately difficult genetics problems. Successful faculty and student subjects organized problems according to genetic concepts which might form the chapter headings in a standard genetics text. The organizational schemes of genetic counselors were not similar to those of the faculty subjects. Both the counselors and the students placed greater emphasis on the knowns and unknowns in the problems. In addition, the counselors emphasized the solution techniques to be used. Based on these findings, it does not appear that the mental schemes used by different sorts of experts in a given discipline to organize their knowledge of content and procedures in that discipline are necessarily designed along abstract/conceptual lines. (CW)

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EXPERTISE, MENTAL REPRESENTATIONS, AND PROBLEM-SOLVING SUCCESS:

A study of the Categorizations of classical genetics problems by biology faculty, genetic counselors, and students

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Paper presented at the annual meeting of the National Association for Research in Science Teaching, Lake Ozark, MO, April 13, 1988.

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EXPERTISE, MENTAL REPRESENTATIONS, AND PROBLEM-SOLVING SUCCESS:
A study of the Categorizations of Classical Genetics Problems by Biology Faculty, Genetic Counselors, and Students

The mental representations used by experts and novices for organizing their knowledge of a discipline have been studied by observing the categorization schemes these subjects produce when presented with a diverse group of problems. These organizational schemes have been studied for problems in physics, mathematics, and computer programming. In the present study, 7 biology faculty who teach genetics, 8 certified genetic counselors, and 26 students were asked to organize a set of 28 classical genetics problems based on how the person would solve them and then to describe their schemes in writing. Separately, subjects solved four moderately difficult genetics problems.

The categorization schemes of the faculty subjects tended to be conceptually based while those of the genetic counselors and students tended to focus on the problem knowns and unknowns even though the counselors were at least as successul at solving genetics problems as were the faculty. Counselors also tended to focus on the procedures to be applied in problem solution while students focused on the verbatim wording of the problem statement. Therefore, not all of the mental schemes used by different types of experts within a discipline to organize their knowledge of that discipline are necessarily designed along abstract/conceptual lines, but may nevertheless contribute to considerable problem-solving success. These findings suggest that subsequent to an individual's initial learning, the learners knowledge structure is modified to reflect the way in which that knowledge is typically applied.

Having an organizational scheme for ones knowledge, however--even a scheme based on lines similar to those used by an expert--does not ensure problem-solving success. Subsequent problem categorization and problem-solving success requires in-depth conceptual and procedural knowledge organized in a manner which facilitates its application.

Finally, this paper considers the impact of these findings on the present understanding of problem solving and on science teaching.

EXPERTISE, MENTAL REPRESENTATIONS, AND PROBLEM-SOLVING SUCCESS: A study of the Categorizations of classical genetics problems by biology faculty, genetic counselors, and students

Introduction

Review of literature

Much of what we understand about problem solving today is based on a large number of studies which compare the problem-solving performance of experts (faculty members or graduate students in the related discipline) and novices (students who have completed or are completing their first introductory college course in the field) (c.f., Larkin, 1980; Newell and Simon, 1972). Some studies (to be discussed below) have also attempted to tap the differences presumed to exist between the ways groups of individuals mentally organize their knowledge of the discipline and of procedures for solving problems within the discipline. Most of these studies have attempted to indirectly assess these differences by analyzing the ways subjects organize groups of written problems. Cluster analyses of these sortings have provided useful information, but these studies are limited by the fact that two individuals may both place a pair of problems in the same group but for very different reasons. Some studies have, therefore, also included various qualitative analyses of the category descriptions provided by the subjects. In mathematics, examples of this research include Chartoff (1977), Hinsley, Hayes, and Simon (1976), Krutetskii (1976), and Silver (1979). Subsequently, attention turned to physics with the classic study of Chi, Feltovitch, and Glaser (1981), followed by others such as Niegemann and Paar, 1986. Categorization of problems of computer programming has also been studied (Weiser and Shertz, 1983).

These studies have typically focused on one or more of the following areas: a) the "problem-solving dimensions" or types of categories that are used to organize problems; b) the relationship between the use of these categories and problem-solving ability and/or expertise; c) the ability to discriminate between problems; and d) the degree of mental processing required.

Problem-solving dimensions. Studies to date have identified a number of very related similarity dimensions. Chartoff (1977) observed that students recognized four similarity dimensions: 1) how the problems are solved, 2) the contextual setting, 3) comparison with a generic problem of the same type, and 4) the question posed by the problem. Similarly, subjects in Silver's 1979 study sorted problems on the basis of mathematical structure, contextual structure, question form, and "pseudostructure" (mutual presence of a measurable quantity). Subjects in the Chi, et al (1981) study used either labels focusing on the problem's "surface structure" (inclined plane problems, pulley problems) or "deep structure" (the underlying physics law or principal applicable to the problem. Within genetics, Stewart (undated) has recently suggested three dimensions: conceptual, cause to effect/effect to cause, and pedigree/non pedigree.

Problem-solving ability, expertise. Of the studies mentioned above, only Silver (1979) considered problem-solving ability. Strong positive correlations were observed between students' sorting based on mathematical structure and various measures of math and verbal abilities, while negative correlations were observed between these abilities and the tendency to sort on the basis of contextual details. The tendency to use question form was negatively correlated with problem-solving performance; the analyses of the tendency to use pseudostructure were conflicting. Chi, et al (1981) found that novice subjects were more likely to use categories which focused on the surface structures in the problem, as opposed to experts who tended to sort problems according to similarities in deep structure. Similarly, faculty experts in the Weiser and Shertz study (1983) sorted problems according to algorithms which they abstracted, while novices sorted according to more "literal features" of the problems. This surface structure/deep structure distinction between experts and novices is therefore assumed to hold true for other disciplines and has become a basic tenet of the present understanding of problem solving.

To date, two findings call this conclusion into question. First, not all the "expert" subject in the Weiser and Shertz study used deep structure criteria for their sorting. Computer-programmer managers, a second group of experts included in that study, grouped problems according to the "kinds of programmer to whom they would give each problem". Second, a recent preliminary study by Maloney (1987) suggests that physics students may focus more strongly on the "question asked and the variables provided than on the specific objects involved."

Ability to discriminate between problems and the degree of mental processing required. Less attention has been paid to these two issues. Chi, et al (1981) observed that three categories used most frequently by their expert subjects each accounted for an average of 33% of all problems while 39% of all novice problems were to be found in a single category. This finding suggested to these authors that "experts are able to 'see' the underlying similarities . . . whereas the novices 'see' a variety of problems that they consider to be dissimilar because the surface features are different." In contrast, Weiser and Shertz (1983) found that the largest four categories of novices typically included fewer problems than did the first four groups of experts.

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The degree of mental processing required has typically been inferred from the time required to complete the sorting task. Both Chi, et al and Weiser and Shertz found that their expert subjects required significantly more time than did novice subjects. No difference was observed between the time requirements or size of groupings of their two expert subgroups.

While the findings of these studies have generally supported each other, the difference in ability to discriminate between problems as measured by the number of problems in the largest problem categories is a matter of concern. Even more troublesome is determining how the Weiser and Shertz observations of programmer managers are to be incorporated into our present understanding of problem solving. The absence of measures of problem-solving success in both these studies is also a notable deficit. One may, of course, presume that Chi and her colleagues assumed that their experts were successful problem solvers and that their novices were unsuccessful. A number of recent studies, however, have questioned the wisdom of equating expertise and success. Experts may be less successful than expected if they are "out of practice" (Good, Bandler, and Kromhout, personal communication). Procedures used by experts (e.g., automatic processing) may also be the result of extended experience more than problem-solving ability. On the other hand, research (c.f., Bodner and McMillan, 1985; Smith and Good, 1984) has identified certain novices who are successful problem solvers. These studies have demonstrated that successful subjects often share more characteristics which distinguish them from unsuccessful subjects than do experts when compared to novices.

Purpose of the Study

The present study was designed to permit the comparison of individuals according to both expertise and problem-solving success and to include two different types of experts within the domain of genetics. Specifically, this study was designed to address the following research questions:

a) How do different types of individuals mentally organize their knowledge about solving problems within a discipline?

b) Are the findings of categorization/mental representation studies in other disciplines true for genetics?

c) In addition to those patterns of problem categorization which distinguish experts from novices, are there patterns of problem categorization which distinguish successful from unsuccessful problem solvers?

Methodology

Data Collection

In this study, 7 biology faculty members who teach genetics, 8 licensed genetic counselors, and 26 students were asked to organize a set of 28 classical genetics problems "based on how you would solve them...in any way that makes sense to you" and then to "circle the keyword(s) in each problem, that is, the words which are important in the organization decisions you make." The time required for each individual was recorded. Upon completion of this task, the subjects were asked to "briefly describe your organization on a sheet of paper", to "give each label you use and the ID numbers of the problems you associate with each." Subjects were also encouraged to give a "brief (one sentence) description of what each of your labels means." Finally, subjects were asked to solve a set of four moderately difficult genetics problems which had been found useful in our earlier studies (Smith and Good, 1984) for meaningfully categorizing subjects as either successful or unsuccessful problem solvers. Problems for the sorting task were drawn from a widely used college genetics textbook (Strickberger, 1976) and have been described elsewhere (Smith and Waterman, 1987). Characteristics of the faculty and students subjects have also been previously reported (Smith and Waterman, 1987).

Most student data was collected in two large group sessions; approximately one to one and one half hours were required to complete the categorization and solution tasks. Five students performed the tasks in smaller makeup sessions. Faculty and genetic counselors received their materials by mail and completed the tasks privately. Early in the project, one faculty member performed the sorting task in a videotaped interview as a pilot study in which the problem set and the data collection procedures were established.

Problem Scoring

The subjects' solutions to each of the four problems were evaluated and scored as correct, essentially correct including only minor error(s), or incorrect. Based on our previous use of these problems (Smith, 1983; Smith & Good, 1984), individuals whose solution of one or more of the four problems was correct (or essentially correct) were classified as "successful". Each problem was also scored on a scale of one to five points for a total possible problem-solving score of 20 points. The procedures used for solution classification and scoring have been previously described (Smith and Good, 1984; Smith and Waterman, 1987).

Analysis

The frequency with which each group paired each problem with every other problem (all possible pairwise permutations of the 28 problems) was computed. For each of the possible 378 pairs, the multiple correlation coefficient was calculated as an indication of how well membership in a subject group predicts whether or not a given problem pairing will be made. Six problem pairs which best distinguished among the subject groups were selected for further study. A modified cluster analysis of these problem pairs was performed. Based on the results of the cluster analysis, a content analysis of all group labels produced by subjects in the study was performed.

In addition, for each subject group the mean number of problem categories, the mean number of problems per category, and the mean sorting time for each subject group were computed. The number of problems included in the largest category of each subject was noted and means computed for each subject group. This procedure was repeated for the second, third, and fourth largest groups and the data were combined. Finally, the average number of individual keywords identified, number of "Q keywords" identified, and number of "chunks" circled per problem were computed. "Q keywords" are words found in the problem question, e.g., "What are the genotypes . . .?" Number of "chunks" refers to the number of circles drawn in a problem statement, since several words may be included in a single circle or "chunk".

Results

Problem-solving Success

The mean problem-solving scores and frequencies of successful individuals in each of the subject groups are provided in Table 1. Compared to the subjects in our previous studies (Smith, 1983; Smith & Good, 1984), problem scores were generally higher for subjects in this study. The anticipated higher proportion of "successful novices" (students) is most likely due to the inclusion of a large proportion of subjects who were upperclassman science majors. Surprisingly, the problem-solving scores of the genetic counselors were higher than those of the faculty subjects. This is probably explained by the fact that the solution of two of the four problems required applying probability concepts which the counselors are more likely to use on a frequent basis.

Insert Table 1 about here.

Categorization of subject groupsings by previously idenetified dimensions

Based on the frequencies with which subjects paired various problems (and the associated correlation coefficients), six problem pairs which appeared to be the best for distinguishing among the various groups of interest were analyzed (Table 2). Problem pairs 20-21 and 14-20 were among those with the highest correlation with problem-solving success. Problems 8 and 26, 16 and 20, 13 and 26, and 8 and 21 were among those with the highest correlation with expertise group. Examples of these problems are provided in Figures 1 and 2. For each of these six pairs, the keywords circled in each problem, the labels used, and the verbal descriptions provided by the subjects in the various groups were studied carefully.

Insert Table 2 and Figures 1 and 2 about here.

Based on the findings of Chi, et al (1981), an attempt was made to categorize each of the group labels as either "superficial" or "deep". This coding scheme could be easily applied to the faculty sorting schemes but was less acceptable for student structures. For example, students sometimes used conceptual labels (such as "sex-linked") implying the use of "deep structure", but in many of the problems assigned to these groups the word/s used to name the concept were not only to be found verbatim in the problem statement, but were also circled by the student. Did such labels represent "deep" or "surface" processing? In addition, many of the genetic counselors' labels were exceedingly difficult to classify, and the superficial/deep coding scheme seemed to be even more arbitrary for this group. Perhaps the strongest suggestion of the inappropriateness of the superficial/deep dichotomy is the unexpectedly large proportion of labels used by the (very successful) counselors which were clearly related to surface features of the problem. For example, 44% of the counselor subjects used one or more category labels which focused on the kind of organism in the problem (plant, animal, human, etc.).

Stewart's "cause to effect/effect to cause" dimension was also considered. In genetics, this difference essentially translates into determining the offspring expected given the mechanism of inheritance vs. determining the mechanism of inheritance from offspring data. A liberal classification of the category labels produced by subjects in this study revealed that only 9% of the faculty labels, 15% of the counselor labels, and 26% of the student labels were related to this dimension.

Identification of Similarity Dimensions

A scheme which would more accurately and completely describe the group labels used by the subjects and provide more insight into the nature of the sortings of individuals in different subgroups was developed. Briefly, the following similarity dimensions were identified:

1) knowns--category label cites the information given (e.g., "pedigree given");
2) unknowns--category label cites the information requested (e.g., "find parents");
3) verbatim--category label includes word/s found verbatim in the problem statement and circled in at least 50% of the problems included in the category;
4) procedural--category label includes an action/procedure/technique to be performed (e.g., "I would draw a

pedigree.");

5) conceptual--category label cites a genetic concept (which is not found verbatim in the problem statement or, if present, is not circled in at least 50% of the problems included in the category);

6) other--category labels that can not classified above (e.g., "general", "miscellaneous", etc.).

This scheme was used to conduct a content analysis of all problem labels (Table 3). Of all categories produced by the subjects, 97% fall into one of the first five dimensions.

Insert Table 3 about here.

Faculty sortings. Several patterns were noted in the analysis of this data (Table 3). As in previous studies, faculty experts tended to sort the problems along very conceptual lines (68% conceptual labels vs. 18% each for students and counselors). In problems 13 and 26 shown in Figure 2, for example, the majority of the faculty labels related to the number of loci involved in the problem ("dihybrid" in this case), linkage, or recombination. Faculty labels in other problems typically focused on one of these concepts or on the mechanism of inheritance involved or independent assortment. The relative emphasis on conceptual groupings in faculty schemes is even more pronounced in those problem pairs, such as 13-26 and 16-21, which distinguish best between the three groups. (Data not shown.) Furthermore, the percentage of conceptual labels in faculty sortings is likely underestimated by the coding procedures which are designed to identify as "verbatim" those labels that appear to be conceptual but are circled verbatim in the related problems. This procedure makes the least assumption about processing that has occurred, resulting in a conservative estimate of conceptual labels. In contrast, the relative proportion of conceptual labels may be inflated for students since labels related to "probability" accounted for 23% of all conceptual student labels but only 3% of faculty conceptual labels. Such "concepts" are not discipline-specific and should perhaps be considered separately.

Student sortings. Students more often focused on the question being asked, the organism involved, and/or the information given, i.e., on the"knowns and unknowns" (students-49%, counselors-60%, faculty-21%). Typical labels include:

S10: "Given results of cross and asked to determine parental genotypes or phenotypes"; and
S12 "Animal problems-explaining the results".
S08: "Alleles here are give [sic] dominant a [sic] recessive, all you have to do is find out stuff about progeny";

Notice the similarity in the "knowns and unknowns" of problems 16

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and 21 (Figure 1) which were paired by 81% of the student subjects. Again, the relative emphasis on these groupings in student and counselor schemes is even more pronounced in those problem pairs which distinguish best between the three groups. (Data not shown.) These trends are further demonstrated in the entire organizational schemes produced by a faculty member and a student and provided as examples in Figure 3.

Insert Figure 3 about here.

Counselor sortings. The sortings of the genetic counselors revealed several unanticipated results. (See Figure 3 for an example.) Instead of resembling their faculty peers, the categorization schemes of the counselors more closely resembled the sortings of the student subjects. Like the students, the counselor subjects tended to focus on the knowns and unknowns in the problem. A typical label is that of Subject G10: "Pedigree given, calculate probabilities". Correlation coefficients for almost all problem pairings were very similar for the student and genetic counselor subjects and were not similar to those calculated for the faculty members. In fact, when pairwise correlations were computed, not one of the 378 pairs was found to distinguish between students and counselors at a correlation coefficient greater than .56 (explained variance = .306), although fourteen such pairs were identified distinguishing between faculty and counselors.

Student/counselor differences. Content analysis of the labels selected by the subjects suggests at least two important distinctions between student and counselor sortings. First, counselors often focused on the procedures to be used in the solution, e.g., drawing a pedigree (when none is given) as an aid to the solution process. Almost no allusion to such procedures is made in the categorization schemes of the other two groups even though the sorting instructions specifically emphasize grouping problems "based on how you would solve them." Second, students appeared to be markedly more influenced by the specific wording of the problem than did the counselors. The "keywords" circled by student subjects were often used verbatim as group labels resulting, for example in S34, in the common grouping of problems which appear to have little in common except that both ask the solver to provide an explanation. (In this case, the word "explain" is circled in each problem in the group.) Similarly, this focus on the words used in the problem statement often resulted in the production of two separate groups which are identified by essentially synonymous terms. For example, student subject S13 sorted problems which asked for the calculation of "probabilities" separately from those which asked for "proportions", and these terms were selected as keywords in every problem included in these groups. Both the increased use of procedural labels by counselors and the increased use of verbatim labels by students were more pronounced in problem pairs which distinguish best between the three groups. (Data not shown.)

Sortings by successful vs. unsuccessful subjects. Comparisons of successful and unsuccessful sortings also produced unexpected results. No consistent patterns could be identified which distinguished between our successful and unsuccessful subjects across the problem set provided. Both the cluster analysis and the subsequent content analysis of the categorization schemes produced by these two groups demonstrated that the distinctions among faculty, counselors, and students were clearly more remarkable than the distinctions between successful and unsuccessful subjects. The observed correlations between various pairings and whether or not the subjects were successful were generally not as high as correlations for expertise group (faculty/student/counselor). Furthermore, all problem pairings which explained a relatively large proportion of the variance (.20 or more) were more often paired by unsuccessful subjects than successful. Differences in group means on a number of other variables to be discussed below (e.g., number of problems per group, number of keywords selected per problem, and the frequency of various label types) were also greater when subjects were compared by expertise than when compared by success. For these reasons, subsequent group comparisons focused on expertise and not on success.

Keywords

In keeping with the tendency for the categories of students and counselors to focus on unknowns in the problem, both groups identified approximately three times as many Q keywords as did faculty (Table 4). Faculty and counselor subjects identified the same average number of all keywords per problem, however, which was less than the number of keywords identified by student subjects (3 and 3, vs. 5).

Insert Table 4 about here.

Chunking

Table 4 also reveals that all three subject groups circled an average of two word groupings per problem. Each circled word group might be considered a chunk of information which the subject recognized as a unit. If so, these results agree with earlier findings in chess that demonstrate that subjects at various levels of expertise attend to the same number of chunks (piece positions) but that the chunks of the more expert subjects include more individual pieces (deGroot, 1965; Simon 1981).

Ability to discriminate between problems

Similar to the findings of Chi, et al (1981), faculty subjects in this study tended to assign fewer problems per group (mean 3.0) than did student subjects (6.1) (Table 5). Counselors produced even larger groupings (mean 5.6). Comparing the number of problems assigned to only the largest group produced by each individual, faculty again have the smallest problem groups (mean 7.0 problems per group), followed by students (8.8) and counselors (11.0) (Table 5). These relative differences are also true for the number of problems accounted for by the three largest groupings combined.

Insert Table 5 about here.

Degree of mental processing required

There were no apparent differences in the mean length of time required by the various expertise subgroups for the sorting task (Table 4).

Miscategorizations

Determining whether or not a single problem should be included in a given category is often impossible because of the subject's use of confusing labels. Clear miscategorizations were found in the organizational schemes of all three subject groups, and they did not seem to be more prevalent in any one group. Five student subjects (S18, 21, 22, 23, 24, and 30) who appeared to have clear miscategorizations were studied for the two problem pairs 12-26 and 16-21. Of the eight errors noted, six (75%) were within conceptual groupings even though only 27% of all student group labels were conceptual.

Parenthetically, it should be noted that several of the subjects produced branching tree organizational structures which were purposely allowed by the instructions given in this experiment. The "sorting into piles" instructions used by Chi, et al. are not conducive to the use of such schemes. The sortings obtained by these investigators therefore may not have reflected the internal organizations of some of the subjects as well as they might have. The more inclusive instructions used in this study seem advisable for use in any further research.

Conclusions

To summarize, the categorization schemes of the faculty subjects tended to be conceptually based while those of the genetic counselors and students tended to focus on the problem knowns and unknowns. The counselors also tended to focus on the procedures to be applied in problem solution while the students focused on the verbatim wording of the problem statement.

If counselors and students employ internal organizations which are grossly similar, why then are the counselors so much more successful than the students? There are at least three reasons. First, the preferential use of procedural labels by the counselor subjects suggests that these individuals not only recognize problem knowns and unknowns but also that they have a set of procedures which they can apply successfully to the problems. Previous research (Smith and Good, 1984) has demonstrated that unsuccessful subjects are frequently inept at applying such problem solution procedures. Perhaps as important as the ability to carry out these procedures is the knowledge of the appropriate problem conditions to which each procedure should be applied. An excellent example of this difference is in the relative use and importance of pedigrees. Students, like faculty and counselors, often grouped problems in which a pedigree was presented, but only genetic counselors grouped together "problems that I would draw a sketchy pedigree to solve" (G10). In such counselor subjects, the procedural knowledge appears to be intimately integrated with the related content knowledge.

Second, the content knowledge of the counselor subjects is likely to be markedly superior to that of the students. The counselors apparently have an excellent understanding of the genetic concepts, their knowledge organized around the ways clients typically present themselves and the procedures which are to be applied.

Third, the lack of focus of the counselors on the verbatim wording in the problem statement which is so common among student subjects suggests that the two groups focus on the problem knowns and unknowns in rather different ways. The smaller number of keywords identified by the counselors suggests that they are less affected by irrelevant information in the problem statement. In addition, some students appear to <u>recognize</u> the problem goal/unknown but have a very limited <u>understanding</u> of what that goal is. This understanding of the problem goal and what that goal shares in common with goals in other problems can be an important basis for recognizing groups or "types" of problems that share similar solution paths. Perhaps the best example of the lack of this understanding is student S25's grouping of a set of problems which asked for expected offspring numbers or ratios into a category labeled "Softcore Problem Solving". She explains:

> I titled this small group as such because these problems asked for my <u>expectations</u> [emphasis added]. Therefore there is no right or wrong answer so to speak (at least for part of the question). These problems all deal with wanting to know the reader's understanding of the "work done" or material given so that he/she can then have an intelligent expectation.

This lack of understanding clearly contributes to the lack of student problem-solving success.

<u>There can be more than one kind of "expertise" within a discipline</u>. Not all of the mental schemes used by different types of experts within a discipline to organize their knowledge of that discipline are necessarily designed along abstract/conceptual lines, but may nevertheless contribute to

considerable problem-solving success. There is no "right" or "wrong" type of organizational scheme, though there are clearly organizations which facilitate the accomplishment of certain tasks/problems better than others.

How are these different organizational schemes to be explained? Research suggests that the structure of the scheme by which a person organizes his/her knowledge about a discipline is most significantly determined first by the understandings and abilities the student brings to the learning situation, the way the learning environment is structured, and by the goal(s) of the learner during the learning process. The findings of this study suggest that <u>an individual's knowledge structure is subsequently modified to reflect the way in which that knowledge is typically applied</u>. Consider first the typical undergraduate student. For many of these individuals, the immediate goal in approaching a homework or test problem is to obtain the correct solution (to make a good grade). This focus on knowns and unknowns parallels the well documented tendency of novices to use means/ends analysis which focuses on reducing the difference between the current position in the problem (current knowns) and the goal state (unknown) (Simon and Paige, 1979). At least for genetics problems, this goal and the prevailing instructional methods apparently lead to organizing memories about problem-solving experience in terms of similarities in the knowns and unknowns of the problems.

Not dissimilarly, the goal for the genetic counselor is to solve the problem/to get the right answer to share with the client. It should be no surprise that counselors would tend to organize their genetics knowledge according to the more "superficial" knowns and unknowns. This is certainly the way the counselor approaches genetics problems daily--not with the concept uppermost in his/her mind--but considering the patient as s/he presents, along with lab and pedigree data which are then collected and analyzed. Based on these "knowns", the "unknown" prognosis and likelihood of recurrence questions must be answered. This conclusion is further supported by the fact that 44% of all the counselor subjects' problem schemes included the labels "mechanism of inheritance to be determined" and/or "mechanism of inheritance given". Only 13% of the faculty subjects and 12% of the students used these labels.

The faculty member, on the other hand, typically approaches the discipline with a considerably different goal in mind. Most faculty would likely acknowledge that whether or not a student correctly solves a given problem is not nearly so important as it is for the student to learn the <u>concept</u> involved. The faculty member invests his/her efforts in organizing the class around the presentation of these concepts. Course texts are also organized around these concepts. Solving problems in class is an adjunct to the goal of conceptual learning, not the primary learning goal itself. For faculty members, this conceptual framework is a powerful tool, but it can also be a kind of blinder. Notice that, even though the subjects were asked specifically to organize the problems according to similarities in how they would solve them, the labels used by the faculty members most often referred to the concepts they try to teach and not the procedures required for problem solution. The findings of Chi, et al (1981) could be similarly interpreted, the physics faculty organizing problems according to physics concepts (e.g., "equilibrium") as opposed to problem-solving procedures (e.g., vector diagrams). As they learn these concepts, students presumably begin to reorganize their knowledge along more conceptual lines.

This difference, like most of those noted in this report, is not an all-or-none phenomenon. Students are learners in the process of acquiring both content and procedural knowledge. The occasional use of various faculty-like conceptual labels by students evidences that this learning is taking place. The considerable success of the mostly upperclassman pre-med student subjects in this study is likely related to their developing conceptual frameworks. This conclusion is further supported by the fact that the "sex-linked" category used frequently by faculty accounted for fully 29% of all student conceptual labels, although this label was only used once in this study by a counselor.

<u>Problem-solving success requires in-depth conceptual and procedural knowledge organized in a manner which facilitates its application</u>. The student use of conceptual labels does not lead to the degree of success noted in our faculty subjects. This lack of student success is presumably related to the previously noted lack of the conceptual and procedural knowledge which must be applied in order to solve a problem once it is categorized. This assumption is supported by the fact that faculty subjects were approximately twice as likely as students to identify as sex-linked two problems that were not explicitly identified as such in the problem statement. Similarly, the majority of student miscategorizations appear to be in the use of conceptual labels which they are presumably in the process of learning. Fully 13 of the 15 conceptual "sex-linked" categories used by students contained one or more miscategorized problems. Thus, while it may be conducive to success to have a certain conceptual framework of the area, it benefits the solver little if s/he cannot properly recognize problems within each class or does not have the knowledge or procedures required to solve problems of that type. In fact, miscategorization could clearly contribute to problem-solving failure. This observation may explain some of the frustration frequently observed in students during the time when they are developing such frameworks in our classrooms.

Therefore, it seems clear that <u>merely having an organizational scheme for one's knowledge--even a scheme based on</u>

lines similar to those used by an expert--does not ensure problem-solving success. First, knowledge (both content and procedural) of appropriate type, breadth, and depth must be resident within that framework. Second, that knowledge must be available, and the solver must be able to apply it in appropriate situations.

As predicted from the 1981 Chi et al study, faculty subjects in this study produced smaller problem groups than did the students, implying that the faculty are more able to discriminate between problems by recognizing the critical aspects of the problem statement. The validity of this conclusion, however, is seriously questioned by the fact that the expert counselor subjects in the study produced group of approximately the same size as those of the student subjects. Given the success of the counselors, it does not appear to be appropriate to assume that the larger size of their problem groupings reflects a basic inability to discriminate between problems. It appears that the differences in size of problem groupings is more a function of the interplay between the conceptual focus of the faculty and the fact that the problems to be sorted were specifically chosen to include at least one or two examples of each of a wide variety of conceptual types. Further research employing different problem sorting sets and random subject sampling should address this issue.

In contrast to previous studies, no apparent differences were noted in the length of time required for the three subject groups to complete the sorting task. Interpretation of the longer times required by experts in these studies as demonstrating the occurrence of an increased mental processing must therefore be reconsidered. In this regard it may be important to recall that other research (e.g.,Ericcson and Simon, 1980) has demonstrated that much of what experts do is tacit and automatic, i.e., does not require deliberate thought. The most casual observer of a chess match between a master and a less experienced player will note that the expert typically moves much more quickly than the novice. This speed, in fact, allows the master to play several lesser opponents simultaneously. The increased expert mental processing conclusion may still be tenable, but the merit of inferring this variable by the length of time required for the sorting task is now in question.

Further study

Finally, our understanding of expertise within given disciplines may be too narrow because researchers have limited their study to faculty experts and student novices. This appears to be the case at least in our understanding of the mental organization of disciplinary knowledge. The further study of non-educator experts may shed surprising new light on problem-solving expertise. The organizational schemes used by various types of experts, how these schemes are developed, how they are affected by the learning environment, and how they are modified by experience may become a valuable new area of research in itself.

The conclusions drawn here call for a considerable reevaluation of the present theory of problem-solving. These findings are based, however, upon a relatively limited number of subjects and must be considered tentative at this time. Further research designed to test these conclusions is being planned. This research will also address many of the questions which arise from this study. Among these are:

a) What is the nature of expertise?
b) Is our research goal to understand expertise or successful problem-solving performance? What are the differences?
c) Is our pedagogical goal to produce experts, successful problem solvers, students who "understand the concepts", etc.?
d) How do mental organizational schemes of disciplinary knowledge develop?

IMPLICATIONS FOR SCIENCE TEACHERS

The conclusions presented above suggest several potentially valuable instructional modifications which can be tested for their utility in the classroom. We will consider four.

First, it seems advisable to <u>invest some instructional effort into helping students develop useful organizational frameworks for their knowledge of problems, content, and procedures</u>. This might entail demonstrating the usefulness of such frameworks and providing practice with feedback at constructing, applying, and evaluating such frameworks. Second, a quick perusal of the <u>organizational scheme and problem categorizations within that scheme made by a student is a simple and efficient way to readily identify concepts which the student has not acquired</u>, e.g., labeling autosomal trait problems as sex-linkage problems. Instructors might assign a categorization exercise for homework in which a set of problems is to be grouped within a given set of categories. This exercise could serve as a valuable formative assessment or could be used as a preassessment for a course which assumes previous genetic understanding.

Third, any problem-solving instruction in a discipline would likely benefit from <u>acknowledging the student goals</u> (e.g., getting "right answers") and how they differ from the instructor's goals (conceptual learning). In the previous suggestions, for example, these frameworks could be presented not as an end in themselves, but as tools which would enhance the students' ability to correctly solve the problem.

Fourth, as the instructor/curriculum planner designs the

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framework in which the conceptual and procedural course content is to be presented, s/he should be explicitly guided by an understanding of how that knowledge is likely to be used by those students after graduation. Wherever possible, this course design should be based on an understanding of the mental frameworks which individuals have actually been observed to use effectively in those goal situations. The effectiveness of implementing such a recommendation would, of necessity, be restricted by heterogeneity in long term student goals. Nevertheless, this type of instructional design is feasible for general education courses designed to produce an "educated citizenry", classes designed to train certain professionals, etc. This is not the same as the longstanding arguments for relevance in course content. These arguments have frequently led to the inclusion of interesting examples and to certain additions to and deletions from the course content. In contrast, we are suggesting that the organization of the course content should reflect the intended uses to which that knowledge is to be put subsequently.

An excellent example of such a curricular organization is already to be found in the field of medical education. During the first two years of medical training, students typically sit in large lecture halls, hear detail-rich, conceptually-based lectures, and are evaluated on their ability to reproduce large amounts of information. Recently, however, the medical education community (especially the Association of American Medical Colleges) has shown considerable interest in a curriculum innovation known as "Problem-based Learning" (Barrows and Tamblyn, 1980). One of the initial concerns which led to the development of PBL was the apparent difficulty which medical students in their clinical years often have in integrating their vast compartmentalized knowledge so as to apply information from various areas to a single case. In other words, students learn medical content in a format which is based on the specialization of the faculty but which essentially ignores the manner in which this knowledge is to be put to use. In contrast, in typical Problem-based Learning curricula the learning experience for first and second year students is designed around individual patient cases. Instead of learning physiology, biochemistry, etc. in separate classes, students learn such information within the context of a case designed to simulate how the physician would be required to address the problem in a presenting patient.

Problem-based Learning has now been implemented either as the school-wide instructional design or as a parallel track in at least seven medical schools around the globe, including McMaster University where it was first conceived and Harvard University. These programs have been subjected to extensive analyses (c.f., the various volumes of the Proceedings of Research in Medical Education Conference), and the results of these analyses have tended to strongly support the value of this educational design. It would appear that educators involved in disciplines other than medicine might also benefit from designing instruction that reflects the manner in which that knowledge will subsequently be applied.

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Figure 1. Problems most frequently paired by student subjects.

Problem 16.

In the following types of matings, the phenotypes of the parents are listed together with the frequencies of phenotypes occurring among their offsporing. Indicate the genotype of each parent.

(a) Parents: AB Rh^+ x O Rh^+

Offspring: 3/8 A Rh^+ : 3/8 B Rh^+ : 1/8 A rh^- :1/8 B rh^-

(b) Parents: A Rh^+ x A rh^-

Offspring: 3/4 A Rh^+ : 1/4 O Rh^+

(c) Parents: B Rh^+ x A rh^-

Offspring: 1/4 AB Rh^+ : 1/4 A Rh^+ : 1/4 B Rh^+ : 1/4 O Rh^+

Problem 21.

What are the genotypes of the following parents?

Phenotypes of Parents		Phenotypes of Offspring (Proportions)			
		A	B	AB	O
(a)	B x B		3/4		1/4
(b)	B x AB		1/2	1/2	
(c)	B x A		1/2	1/2	
(d)	B x A	1/4	1/4	1/4	1/4
(e)	B x AB	1/4	1/2	1/4	
(f)	B x O		1		
(g)	B x O		1/2		1/2

Figure 2. Problems most frequently paired by faculty subjects.

Problem 13.

In corn the seeds can be colored or white, nonshrunken or shrunken. Each of these characteristics is determined by a separate pair of genes, C and c and Sh and sh. Hutchinson crossed a homozygous colored shrunken strain (CCshsh) to a homozygous white nonshrunken strain (cc ShSh) and obtained a heterozygous colored nonshrunken F_1. The F_1 was backcrossed to a homozygous recessive white shrunken stock and the progeny were as follows:

	No. plants
colored shrunken	21,379
white nonshrunken	21,096
colored nonshrunken	638
white shrunken	672

What is the recombination frequency between these two genes?

Problem 26.

In corn a pair of genes determines leaf shape and another pair determines pollen shape. A ragged-leafed plant with round-pollen was crossed to a ragged-leafed plant with angular-pollen, and the resultant progeny were classified as follows:

Class l:	186 ragged-leaf round-pollen
Class 2	174 ragged-leaf angular-pollen
Class 3:	57 smooth-leaf round-pollen
Class 4:	63 smooth-leaf angular-pollen
Total	480

(a) Using alphabetical letters of your choice, designate the genes for the different leaf and pollen characteristics. (b) On the basis of the symbols given in (a), provide genotypes for the two parents. (c) According to your hypothesis what numbers would you have expected for each of the four clases of progeny?

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Figure 3. Example problem categorization schemes produced by faculty, student, and genetic counselor subjects

Faculty subject F11

Monohybrid; Dom/Rec
Trihybrid; Dom/Rec
Monohybrid; Multiple Allele
Monohybrid; Inc. Dominance
Monohybrid; Sex-Linked
Dihybrid; Lethal
Dihybrid; Multiple Allele/Dom-Rec
Monohybrid; Lethal
Pedigree
Dihybrid; Dom/Rec
Dihybrid; Multiple Allele
Differentiating Between Types of Crosses
Dihybrid; Linkage

Student subject S32

1. Problems dealing with sex linked genes. (Problem 1 may also be grouped with those problems asking for probability, and problem 19 may also be grouped with those problems asking for proportions.)

2. Problems all dealing with phenotypes and/or phenotypic proportions.

3. Problems ask for an explaination of the problem. (Problems 23 & 28 may be sub-grouped together since they both deal with mutations.)

4. Problems 4, 6, 7, 15, & 20 deal with a pedigree. (Problem 7 may futher be grouped with questions dealing with proportions, and Problem 15 may be grouped with others dealing with probability.)

5. Problems 8, 16, 21, 25, & 26 ask for the genotypes of parents.

6. Problems deal with recombination.

7. Problems deal with probability.

Genetic counselor subject G03

- Questions with Genotypes known
  - Phenotype: Genotype ratios do crosses
  - Known inheritance
- Questions with Phenotypes, not known genotypes
  - Making assumptions Re: Dom., Recess., x-linked (Try out different patterns.)
  - Draw out Punnett squares or crosses known dom. or recess. (inheritance pattern problems)

Table 1. Problem-solving success of subjects in the three subgroups.

Subject Group	#	$\bar{X}$ Score	% Successful*
Faculty	7	14.9	100
Genetic Counselors	8	18.3	100
Students	26	9.7	65

* Solution to one or more of the four problems was correct (or essentially correct.)

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Table 2. Frequency of pairing of selected problems and related explained variance for subjects grouped by expertise and by problem-solving success.*

Problem Pair	Frequency of pairing by			F/S/GC r^2	Frequency of pairing by		Su/Un r^2
	Faculty	Students	Genetic counselors		Successful Subjects	Unsuccessful Subjects	
8, 26	0	.52	0	.314	.25	.50	.05[illegible]
16, 21	0.29	.81	1.00	.309	.71	.88	.024
13, 26	0.86	.24	0.25	.258	.39	.25	.015
8, 21	0.29	.86	0.50	.250	.57	1.00	.143
14, 20	0	.24	0	.115	.04	.50	.360
20, 21	0	.19	0	.089	.00	.50	.494

*Does not include 5 student subjects recently added to the study. (These subjects are included in all other discussion.)

Table 3. Content analysis of all category labels produced (all subjects).

Category Label	Students (%)	Genetic Counselors (%)	Faculty (%)
Knowns	18	30	15
Unknowns	31	30	6
Verbatim	29	9	7
(KUV total)	78	69	27
Procedural	2	13	2
Conceptual	18	18	68
Other	2	0	2

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Table 4. Variables related to sorting behavior and keyword selection.

	Students	Genetic Counselors	Faculty
$\overline{X}$ # keywords/problem	5	3	3
$\overline{X}$ # Q keywords/problem	1.5	1.3	.5
$\overline{X}$ # chunks	2	2	2
$\overline{X}$ sorting time (min.)	24	26	27

Table 5. Number of problems in subject groupings.

Subjects	$\overline{X}$ # of problems			
	per category	in largest category	in 3 largest categories	in 4 largest categories
Faculty	7.0	15.8	18.8	3.0
Genetic Counselors	11.0	22.4	25.4	5.6
Students	8.8	19.8	23.4	6.1

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