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REPRESENTATION OF PHYSICS KNOWLEDGE BY EXPERTS AND NOVICES.(U)
MAR 80 M T CHI, P J FELTOVICH, R GLASER   N00014-78-C-0375

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REPRESENTATION OF PHYSICS KNOWLEDGE

BY EXPERTS AND NOVICES

Michelene T.H. Chi, Paul J. Feltovich, and Robert Glaser

Learning Research and Development Center

University of Pittsburgh

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21 March 1980

Technical Report No. 2

This research was sponsored by the Personnel and Training Research Programs, Psychological Sciences Division, Office of Naval Research, under Contract No. N00014-78-C-0375, Contract Authority Identification Number, NR 157-421.

This report is issued by the Learning Research and Development Center, supported in part by funds from the National Institute of Education (NIE), United States Department of Health, Education, and Welfare.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER 14 TR-1 Technical Report No. 2	2. GOVT ACCESSION NO. AD-A084452	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) REPRESENTATION OF PHYSICS KNOWLEDGE BY EXPERTS AND NOVICES		5. TYPE OF REPORT & PERIOD COVERED Tecnical Report
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Michelene T. H. Chi, Paul J. Feltovich and Robert Glaser, Learning Research and Development Center, University of Pittsburgh		8. CONTRACT OR GRANT NUMBER(s) 15 N00014-78-C-0375
9. PERFORMING ORGANIZATION NAME AND ADDRESS Learning Research and Development Center University of Pittsburgh Pittsburgh, PA 15260		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR 157-421/3-3-78 (458)
11. CONTROLLING OFFICE NAME AND ADDRESS Personnel & Training Research Programs Office of Naval Research (Code 458) Arlington, VA 22217		12. REPORT DATE 11 21 Mar 1980
		13. NUMBER OF PAGES 58
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 49		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This research was also supported by the Learning Research and Development Center, supported in part by funds from the National Institute of Education (NIE), United States Department of Health, Education, and Welfare.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Categorization
Expert-novice
Knowledge representation
Physics problem solving
Protocol analysis
Schemata
Sorting

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The studies reported here investigate the representation and organization of physics knowledge in experts and novices. Four experiments investigate (1) the existence of schemata for physics problems, (2) qualitative and quantitative differences in schemata types used by experts and novices, (3) differences in the content of these schemata, and (4) features in the physics problems that activate problem representations. Results obtained from problem sorting tasks and protocol analysis reveal that novices and experts begin → next page

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S/N 0102-LF-014-6601

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20. with specifiably different problem representations depending on the structure of their knowledge. The initial representation and subsequent approach to problem solution used by experts is based on physics principles abstracted from a problem, while novices base their representation and approaches on the problem's literal features.

Abstract

The studies reported here investigate the representation and organization of physics knowledge in experts and novices. Four experiments investigate (1) the existence of schemata for physics problems, (2) qualitative and quantitative differences in schemata types used by experts and novices, (3) differences in the content of these schemata, and (4) features in the physics problems that activate problem representations. Results obtained from problem sorting tasks and protocol analysis reveal that novices and experts begin with specifiably different problem representations depending on the structure of their knowledge. The initial representation and subsequent approach to problem solution used by experts is based on physics principles abstracted from a problem, while novices base their representation and approaches on the problem's literal features.

Knowledge representation is a central issue in most investigations of problem solving skill in rich knowledge domains, but it is seldom analyzed systematically. More often than not, investigators assume that some organization of knowledge is present, and proceed to study the manner in which this knowledge is processed. Thus most of the work to date on expert-novice differences has focused attention on the processes of problem solving that differentiate a novice from an expert. In physics, this kind of research is illustrated by the work of Simon and Simon (1978) and Larkin, McDermott, Simon and Simon (in press). The research we describe here explores the organization and representation of knowledge in memory. We assume that differences in the organization of knowledge in experts and novices lead to differential problem representation. Hence, we make a distinction between the representation of knowledge in memory, and the form of the representation of the problem, e.g., words, diagrams, and/or equations (McDermott & Larkin, 1979). We further assume that the quality of the initial problem representation is constrained and guided by the complexity, completeness, and organization of the knowledge representation in memory. Finally, we assume that the quality of this initial problem representaion determines the ease and manner in which an exact problem solution can be searched and executed.

There are several ways one can capture the organization of knowledge in memory. One method is to examine the problem solvers' initial representation of the problem, and make inferences about their knowledge organization. Another method is to probe their knowledge directly, outside of a problem solving context. We used various empirical techniques of this sort in the attempt to capture experts' and novices' organizations of knowledge in physics. For these studies, the form of knowledge representation that we will adopt is a schema. A schema is an active data structure consisting of a network of interrelated components, which themselves are other schemata (Rumelhart & Ortony, 1977). An important property of schema systems is that they are hierarchical: That is, a schema can depend on lower level subschemata, and itself can be subschema for higher level schemata. Another important property of schemata is that they specify variables that can be instantiated in particular problem situations.

Our first research goal was to see if schemata, representing categories of problems, exist in knowledge structures of expert and novice physicists. There are some findings in the literature that suggest that schemata for problem types exist, and that these schemata direct problem solving. For example, the groupings (chunks) found in expert's perceptions of a chess board is taken as evidence that a choice between chess moves (analogous to physics solutions) results from direct association between move sequences and a knowledge representation for configurations in the board (Chase & Simon, 1973). Likewise, the forward-working strategy in physics problem solving reported by Larkin (1979) and Simon and Simon (1978) indicates that the experts' problem solving may be driven by schemata. Finally, Hinsley, Hayes, and Simon (1962) have found that schemata for problem types exist for simple algebra word problems.

Our initial interest then, was twofold: (1) We wanted to see if schemata of problem types exist for physics problems and how they are used in the initial encoding of problems; and (2) whether the nature and underlying bases of these schemata are different for experts and novices. Our ultimate goal is to understand the implications of schemata for problem solving, particularly in the context of the development of expertise.

Study One: Problem Sorting

In our first study, using a sorting procedure, we asked eight advanced graduate students (experts) and eight undergraduates who had just completed a semester of mechanics (novices) to categorize 24 problems selected from chapters five through twelve of Halliday and Resnick (1974), the text used in the course. Instructions were to sort the 24 problems into groups based on similarities in how they would solve them. They were permitted to use as many categories as they wished. As a test of consistency, they were asked to re-sort their problems after the first trial. Following this, they were asked to explain why the problems in each of their groupings were sorted together.

Basis of Representation. The results of the sorting task indicate that the categories into which the experts and novices sorted the problems are qualitatively dissimilar. In particular, problems grouped together by the novices have similar surface structures. By "surface structures" we mean either (a) the objects referred to in the problem, e.g., a spring or an inclined plane, (b) the untransformed physics terms mentioned in the problem statement (e.g., friction), or (c) the visual representation or diagram depicting the physical configuration described in the problem. Figure 1 gives examples of diagrams that can be drawn for two pairs of problems, each of which was consistently grouped together by all eight novices, as determined by the clustering analysis (Chi & Glaser, 1979). Each pair of problems contains the same object components--circular disks in the upper pair and blocks on an inclined plane for the lower pair.

The suggestion that these surface structures are the bases of the novices' representations of these problems can be confirmed by examining subjects' verbal descriptions for the categories which include these problems. Sample category descriptions are given in the figure. The novices' explanations indicate that they grouped the top two problems together because both involve "rotational things" and the bottom two together because they both involve blocks on an inclined plane.

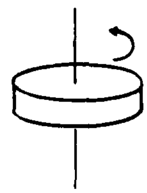
It is important to reiterate that the surface features may involve either the words given in a problem or the corresponding diagrams. The presence of a keyword such as "friction" may be a sufficient reason for the novices to classify problems as similar. However, the novices were also capable of going somewhat beyond the word level into the visual representation to classify the problems. For example, in the problem statements for the top pair of problems in Figure 1, one was referred to as a "merry-go-round," but the other problem was referred to as a "rotating disk."

For experts, surface features do not seem to be the basis for categorization. Figure 2 shows the visual representations of two pairs of problems that the experts (seven of eight subjects for the top pair and six of the eight subjects for the bottom pair) judged similar in the solution method they would use. No visual similarity is apparent within each pair. It is the verbal justifications (see Figure 2) of the experts for these classifications that reveal the basis for similarity. The top pair of problems can be solved by application of the Energy Laws while the bottom pair is better solved by application of Newton's Second Law, F=MA. If "deep structure" is defined as the underlying physics law applicable to a problem, then it seems clear that the deep structure is the basis by which experts group the problems. The actual wording of a physics problem seldom mentions the underlying physical law. Thus, it appears that the determination of the deep structure requires transformation of the surface features of the problem.

Diagrams Depicted from Problems Categorized by Novices within the Same Groups

Novices' Explanations for Their Similarity Groupings

Problem 10 (11)

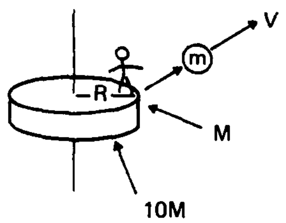


Novice 2: "*Angular* velocity, *momentum*, circular things"

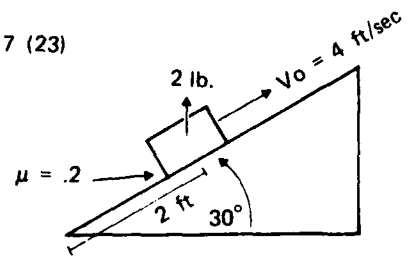
Novice 3: "*Rotational* kinematics, *angular* speeds, *angular* velocities"

Novice 6: "Problems that have something *rotating; angular* speed"

Problem 11 (39)



Problem 7 (23)



Novice 1: "These deal with blocks on an *incline plane*"

Novice 5: "*Inclined plane* problems, coefficient of *friction*"

Novice 6: "Blocks on *inclined planes* with angles"

Problem 7 (35)

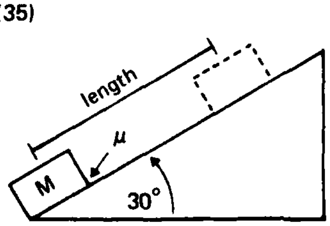
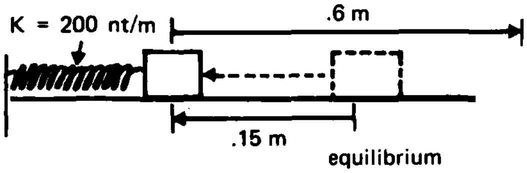


Figure 1. Diagrams depicted from two pairs of problems categorized by novices as similar and samples of three novices' explanations for their similarity are provided. Problem numbers given represent chapter, followed by problem number from Halliday and Resnick (1974).

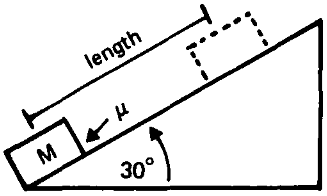
Diagrams Depicted from Problems Catergorized by Experts within the Same Groups

Experts' Explanations for Their Similarity Groupings

Problem 6 (21)



Problem 7 (35)

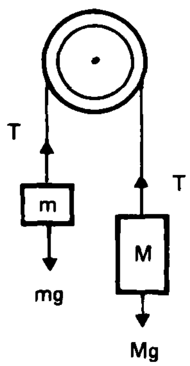


Expert 2: *"Conservation of Energy"*

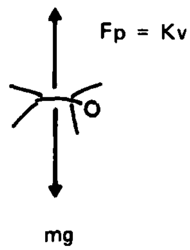
Expert 3: *"Work-Energy Theorem.* They are all straight-forward problems."

Expert 4: "These can be done from energy considerations. Either you should know the *Principle of Conservation of Energy*, or work is lost somewhere."

Problem 5 (39)



Problem 12 (23)



Expert 2: "These can be solved by *Newton's Second Law"*

Expert 3: "F = ma; *Newton's Second Law"*

Expert 4: "Largely use F = ma; *Newton's Second Law"*

Figure 2. Diagrams depicted from pairs of problems categorized by experts as similar and samples of three experts' explanations for their similarity are provided. Problem numbers given represent chapter, followed by problem number from Halliday and Resnick (1974).

Analysis of Categories. Analysis of the categories used by the two groups yields further insight into the basis of problem representation. Quantitative measures showed certain similarities. The two groups were equal in the number of categories they used, 8.6 for the novices and 8.4 for the experts, although for each group, the majority of the problems fell into three to four major categories. Across expert subjects, the four largest categories used by each subject accounted for 80.3% of the problems, while in the novice group the four largest categories used by each subject included 73.5% of the problems.

Differences between expert and novice sorts were especially apparent in the qualitative nature of the categories of the two groups. Tables 1 and 2 show the category descriptions used by more than one expert or novice. These category labels apply to all member problems within each of their sorted piles.[1] (When multiple descriptors across subjects were treated as equivalent in constructing the tables, these are given in parentheses.) Three sets of data are given for each category. The first column shows the number of subjects (of eight) who used the category. The second shows the average size of the category among subjects who used it. The third gives the total number of problems (out of 192, 24 problems for each of 8 subjects) accounted for by the category.

There are several things to note about these data. First, there is little overlap between expert and novice categories. Only five of

20 distinct categories are shared by the two groups (shared categories are marked with an asterisk). Second, if one considers the four predominant categories (the upper four in the Tables) in each subject group (accounting for 61% of the problems among experts, 43% among novices), the only overlap is in the category "*angular motion*." In particular, for these predominant classifications, the novices' descriptions are mostly objects and other surface characteristics of problems, whereas descriptions given by experts all involve laws of physics. Third, there are differences between novices and experts in the distribution of the problems across categories which suggest greater variability in novice classifications. That is, experts classify 53% of their problems into three major categories, whereas novices exhibit a sharp drop after classifying 20% of their problems into a single category. One might speculate that this occurs because the physics laws and principles used by experts "cut across" disparate surface configurations while the variety of representations of the novices is limited only by the number of different ways problems are configured and stated.

To summarize, the results of this initial study suggest that schemata of problem types do exist in the knowledge structures of experts and novices, and that the nature of these schemata are generally not the same for experts and novices. Experts represent the problems on the basis of the physical laws involved, whereas novices tend to represent the problems on the basis of the problems' surface features.

Table 1

Expert Categories

Category Labels	Number of Subjects Using Category Labels	Average Size of Category	Number of Problems Accounted for
Second law	6	6.0	36
Energy principles (Conservation of Energy considerations, Work-Energy Theorem)	6	5.5	33
*Momentum principles (Conservation of Momentum, Conservation of Linear Momentum, momentum considerations)	6	5.0	30
*Angular motion (angular speed, rotational motion, rotational kinematics, rotational dynamics)	6	3.0	18
Circular motion	5	1.6	8
*Center of mass (center of gravity)	5	1.4	7
Statics	4	1.0	4
Conservation of Angular Momentum	2	1.5	3
*Work (work and kinetic energy, work and power)	2	1.5	3
Linear kinematics (kinematics)	2	1.5	3
Vectors	2	1.0	2
*Springs (spring and potential energy, spring and force)	2	1.0	2

Note. * indicates the categories used by both novices and experts.

Table 2

Novice Categories

Category Labels	Number of Subjects Using Category Labels	Average Size of Category	Number of Problems Accounted for
*Angular motion (angular velocity, angular momentum, angular quantities, angular speed)	7	5.6	39
*Springs (spring equation, spring constant, spring force)	6	2.8	17
Inclined planes (blocks on incline)	4	3.8	15
Velocity and acceleration	2	5.5	11
Friction	2	5.0	10
Kinetic energy	4	2.0	8
*Center of mass (center of gravity)	5	1.4	7
Cannot classify (do not know equations, do not go with anything else)	4	1.8	7
Vertical motion	2	3.5	7
Pulleys	3	2.0	6
*Momentum principles (Conservation of Momentum)	2	3.0	6
*Work (work, work plus second law, work and power)	4	1.0	4
Free Fall	2	1.0	2

Note. * indicates the categories used by both novices and experts.

Study Two: Sorting Replication

If our analyses and interpretations in the previous study are accurate, then we should be able to replicate the findings, and further, to predict how a given subject might categorize a given problem. In a second study, we replicated the initial sorting study with one major change in procedure. A new set of 20 problems was constructed in which surface features are roughly crossed with applicable physics laws. Table 3 shows the problem numbers and the dimensions on which these problems were varied.[2] The left column indicates the objects and entities that were described in a problem. The three right headings are basic laws that can be used to solve problems. Figure 3 shows an example of a pair of problems that contain the same surface structure but different deep structure. In fact, they are identical except for the question asked. Our prediction is that novices will group together problems that have the same surface structure, regardless of the deep structure, and experts will group together those problems with similar deep structures, regardless of the surface structure. Individuals of intermediate competence should exhibit some characteristics of each.

Table 4 shows the groupings of a novice who completed one course in mechanics. This novice's classification is based entirely on the surface structures of the problems. He collapsed problems across the physics laws, as was predicted. For example, in Group 1, Problem 2 is a momentum problem and Problem 15 is a force problem; for the four

Table 3

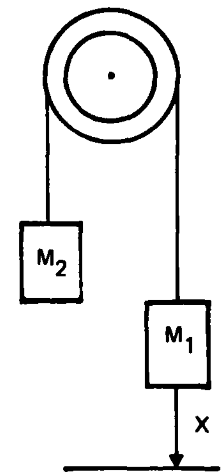
Problem Categories

Surface Structure	Principles: Forces	Energy	Momentum (Linear or Angular)
Pulley with hanging blocks		20†	
	11	19†	
	14*	3*†	
Spring		7	
	18	16	1
			17
		9	6+
Inclined Plane	14*	3*†	
		5	
Rotational	15		2
			13
Single hanging block	12		
Block on block	8		
Collisions (Bullet-"Block" or Block-Block)			4
			6+
			10+

Note. * Problems with more than one salient surface feature. Listed multiply by feature.
† Problems that could be solved using either of two principles, energy or force.
+ Two-step problems, momentum plus energy.

No. 11 (Force Problem)

A man of mass M_1 lowers himself to the ground from a height X by holding onto a rope passed over a massless frictionless pulley and attached to another block of mass M_2. The mass of the man is greater than the mass of the block. What is the tension on the rope?



No. 18 (Energy Problem)

A man of mass M_1 lowers himself to the ground from a height X by holding onto a rope passed over a massless frictionless pulley and attached to another block of mass M_2. The mass of the man is greater than the mass of the block. With what speed does the man hit the ground?

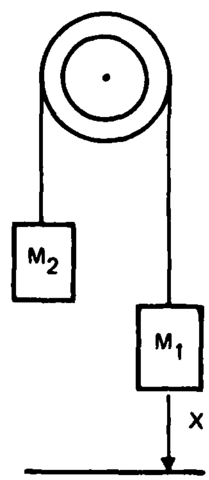


Figure 3. Examples of problem types.

problems in Group 2, 11 and 12 are force problems and 16 and 19 are energy problems. The two problems in group 4, classified by the subject as "Conservation of Energy," were problems purposely constructed as additional tests of "surface dependence" in novices. While both have energy "cover stories" in that they are stated in terms of energy, the major principle in each is momentum conservation and Problem 13 probably could not be done using energy laws.

Table 5 shows the groupings of a physics graduate student. He classified the problems according to the underlying physics laws. In addition, he used only the three categories specified a priori in Table 3. However, four of his classifications are discrepant with our principle analysis, as indicated in Table 3. Possible explanations for these discrepancies include limited subject time with problems or "error" in our classification of applicable principles.

Table 6 shows the categories of a physics professor who sorted the problems after having spent considerable time thinking about how he would solve each problem in conjunction with a different task (reported in Study Four). Hence, it is likely that this subject serves as a good test of whether our prior analysis is consistent with an expert's point of view. Only one problem, (9), is sorted according to a different principle, while an additional problem, (17), is considered a "two-step" problem.

Table 4

Problem Categories and Explanations for Novice H. P.

Group 1:	2, 15	"Rotation"
Group 2:	11, 12, 16*, 19	"Always a block of some mass hanging down"
Group 3:	4, 10	"Velocity problems" (collisions)
Group 4:	13†, 17†	"Conservation of Energy"
Group 5:	6, 7, 9, 18	"Spring"
Group 6:	3, 5, 14	"Inclined plane"
Groups 7, 8, 9 were singletons		

Note. * Problem discrepant with our prior surface analysis as indicated in Table 3
† Problems disrepant with our prior principles analysis as indicated in Table 3.

Table 5

Problem Categories and Explanations for Expert G. V.

Group 1:	3, 9, 2†, 17†, 20, 5, 7, 19, 16	"Conservation of Energy"
Group 2:	13, 4, 10, 6, 15†, 1, 18†	"Conservation of Linear and Angular Momentum"
Group 3:	8, 12, 14, 11	"Statics problems or balance forces"

Note. † Problems discrepant with our prior principles analysis.

Table 6

Problem Categories and Explanations for Expert V. V.

Group 1:	2, 13	"Conservation of Angular Momentum"
Group 2:	18	"Newton's Third Law"
Group 3:	1, 4	"Conservation of Linear Momentum"
Group 4:	19, 5, 20, 16, 7	"Conservation of Energy"
Group 5:	12, 15, 9†, 11, 8, 3, 14	"Application of equations of motion" (F = MA)
Group 6:	6, 10, 17	"Two-step problems: Conservation of Linear Momentum plus an energy calculation of some sort"

Note. † Problem discrepant with our prior principles analysis.

Table 7

Problem Categories and Explanations for Advanced Novice M. H.

Group 1:	*14*, *20*	"Pulley"
Group 2:	1, *4*, *6*, *10*, 12†	"Conservation of Momentum" (collision)
Group 3:	*9*, 13†, *17*†, *18*†	"Conservation of Energy" (springs)
Group 4:	*19*, *11*	"Force problems which involve a massless pulley" (pulley)
Group 5:	*2*, *15*†	"Conservation of Angular Momentum" (rotation)
Group 6:	*7*†, *16*†	"Force problems that involve springs" (spring)
Group 7:	8, *5*†, *3*	"Force problems" (inclined plane)

Note. Italic numbers mean that these problems share a similar surface feature, which is indicated in the parentheses, if the feature is not explicitly stated by the subject.
† Problems discrepant with our prior principles analysis.

What would an individual of intermediate competence do? Table 7 shows the groupings of an advanced novice with four years of physics courses. His representations of the problems are characterized by the underlying principles in an interesting way. These principles are qualified and constrained by the surface components included in the problems. For example, instead of classifying all the Force problems together (Groups 4, 6 and 7), as did the expert, he explicitly separated them according to surface entities of the problems. In other words, although he did not strictly group problems by physics laws, neither did he uniformly group them according to surface features, that is, Groups 3 and 6 were separated even though they both involved springs. In addition, his principle-groupings were substantially discrepant with our prior analysis and that of expert V.V. (Table 6).

Figure 4 uses a hierarchical representation to depict a portion of our problem categories as shown in Table 3. One interpretation of this advanced novice's performance, using such a tree analysis, is that he has not developed some of the middle-level branches or relations. That is, he knows that Problems 3 and 5 (Group 7 in Table 7) involve an inclined plane, and that some inclined plane problems can be solved by the Force Law. What he has not developed is the knowledge that certain inclined plane problems (Problems 3 and 5 in this case) can also be solved by the Conservation of Energy Law. Hence, he lacks the knowledge needed to connect the Inclined Plane node with the Energy Law node.

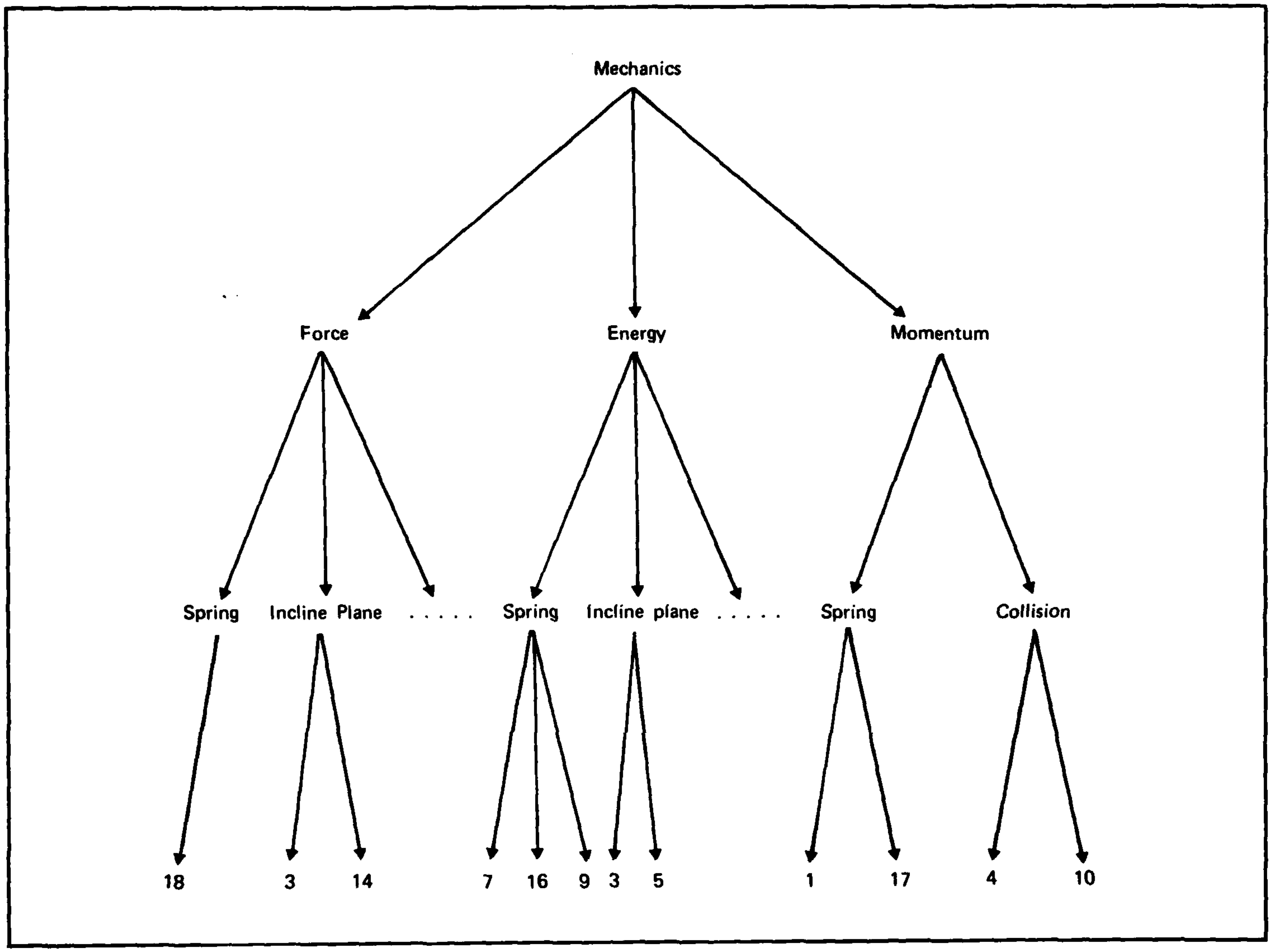


Figure 4. Hierarchical representation of problems according to surface and deep structures.

On the basis of the sorting replication study, we can conjecture a developmental learning process of the following sort. For the beginning student, solution methods are very closely tied to the surface level appearance of problems. As basic physics principles are slowly incorporated into the repertoire, these more general solution methods are still bound to particular kinds of problems; for example, the student may learn that Force Law is often useful in problems involving inclined planes.[3] However, as expertise is acquired there is a liberation of solution methods from those based on surface problem features to those based on principles. This higher level of problem representation requires the abstraction, or transformation, of problem features into principles that cut across surface forms. More will be said about this later.

To summarize the second study, we were able to replicate the initial finding that experts represent physics problems by the laws involved, whereas novices represent physics problems by the physical form of the problem. Furthermore, with learning, advanced novices will begin to represent problems by the underlying laws with gradual release from dependence on the physical characteristics of the problems. However, lacking certain knowledge, their representation is still constrained by surface features.

Study Three: Concept Elaboration

The two foregoing studies indicated to us that, first, schemata are a reasonable way to represent subjects' knowledge of physics problem types, and second, that the schemata of the experts are principle-oriented, whereas the schemata of the novices are object-oriented. In order to verify that these schemata are indeed different, it was necessary to further examine their content. Our next study addressed this question.

Two experts (M.G., M.S.) and two novices (H.P., P.D.) were asked to elaborate on the 20 prototypical concepts that subjects in the first study had used to describe their classifications. These concepts ranged from those provided by experts (e.g., Newton's Second Law, see Table 1), to those provided by novices (e.g., block on incline, see Table 2). Subjects were presented with a concept such as "inclined plane," and given three minutes to tell (a) everything they could think of about it; and (b) how a problem involving the concept might be solved. After this initial open-ended elaboration, the subjects were asked a series of six questions about the concept, such as what a diagram of a problem with an inclined plane might look like, what the possible unknowns in a problem involving an inclined plane might be, what type of equations might be used, and so on.

The results of one expert's (M.G.) and one novice's (H.P.) protocols on their initial three minutes elaboration of the inclined plane are diagramed in Figures 5 and 6. The network representation shown in Figure 5 indicates that the novice's schema for an object concept such as an inclined plane is very well developed, containing numerous variables that can be instantiated. These variables include: the angle that the plane is inclined with respect to the horizontal, whether there is a block resting on a plane, and the mass and height of the block. Other variables mentioned by the novice include the surface property of the plane, whether or not it has friction, and if it does, what the coefficients of static and kinetic friction are. The novice also discusses possible forces that may act on the block such as possibly having a pulley attached to it. The novice never discusses any physics principle until the very end, where he mentions the pertinance of Conservation of Energy. Moreover, this principle was elicited in a very specific context, i.e., in a situation in which "you know the height of the block and the length of the plane."

The casual reference to the underlying physics principle given by the novice in the previous example is in marked contrast to the expert's protocol in which she immediately mentions alternative basic physics principles, Newton's Force Laws and Conservation of Energy, that may come into play for problems containing an inclined plane (see Figure 6 for a diagram of the expert's protocol). As we have depicted on Figure 4, inclined plane problems can sometimes be solved using an Energy Conservation Principle, and at other times, the Force Laws.

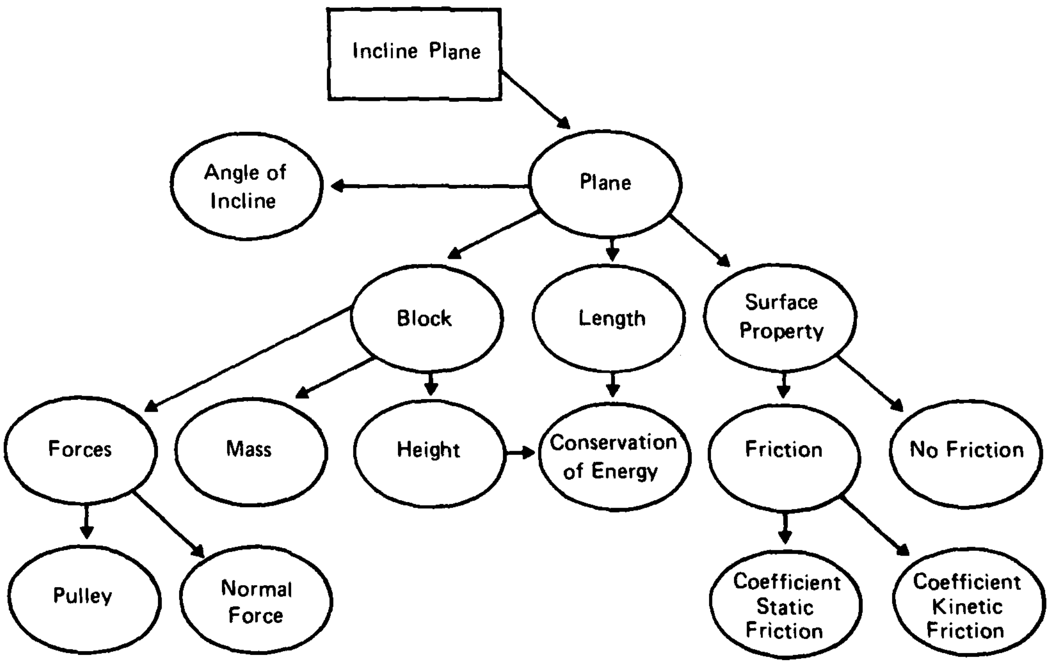


Figure 5. Network representation of Novice H.P.'s schema of an inclined plane.

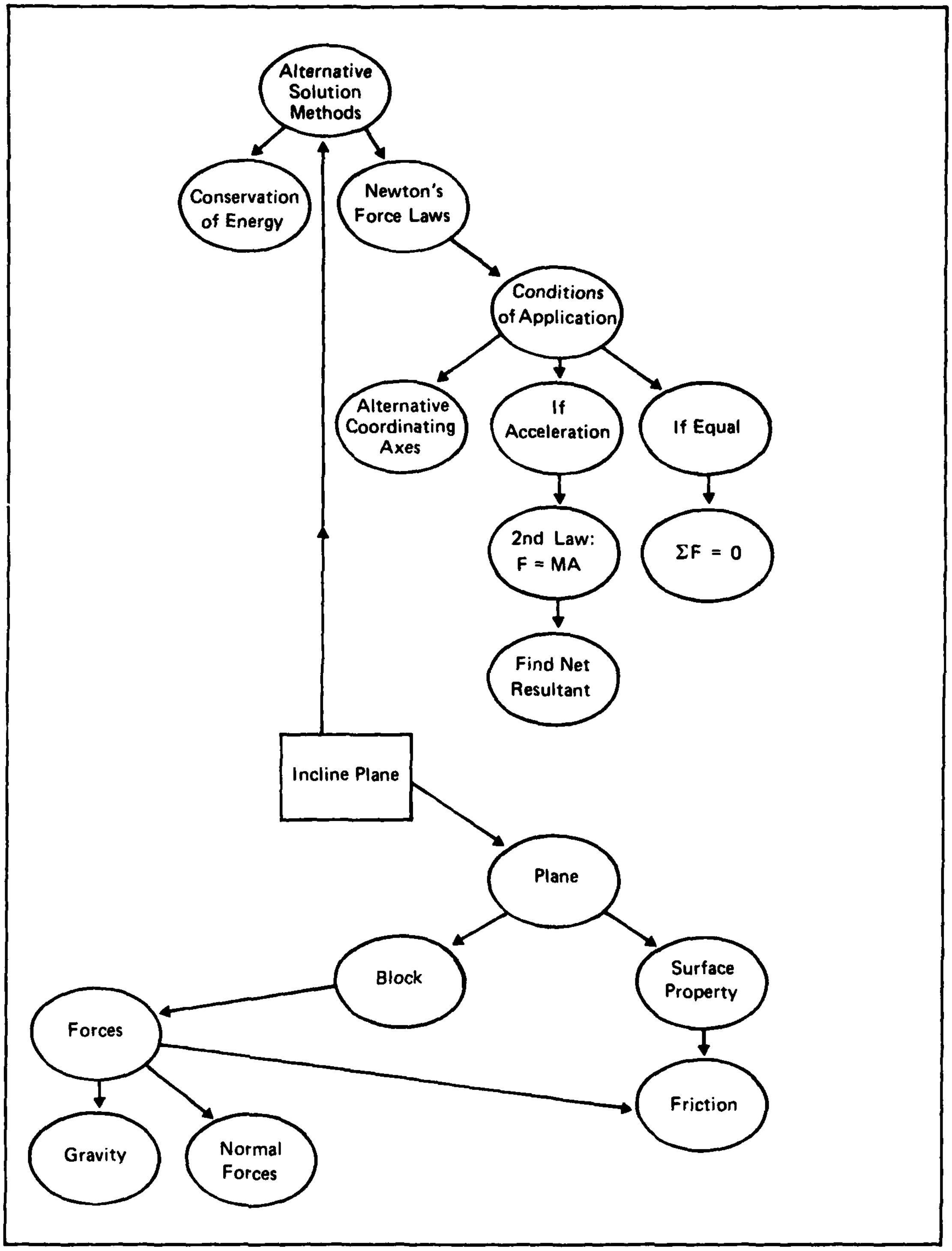


Figure 6. Network representation of Expert M.G.'s schema of an inclined plane.

Hence, it is not surprising that these two basic principles are mentioned by the expert as possible laws to govern the solution of such problems. Another distinction in the expert's knowledge is that she not only mentions the basic physics principles, but also the conditions under which they can be applied. Therefore, the expert appears to have associated with her principles procedural knowledge about the applicability of the principles.

After her elaboration of the principles and the conditions of their applicability to inclined plane problems (depicted in the top half of Figure 6), Expert M.G. continued her protocol with descriptions of the structural or surface features of inclined plane problems (see lower half of Figure 6), much like the description provided by Novice H. P. in Figure 5. Hence, it appears that the expert possesses additional knowledge that is not available to the novice--knowledge that is principles related.

Convergent evidence for the above claim about the expert's knowledge of the conditions of applicability of principle comes from an earlier study (Chi and Glaser, 1979) in which expert and novice subjects were asked to summarize chapter 5 from Halliday and Resnick (1974), a chapter which includes an introduction to Newton's Laws. The results of analyses of subjects' summaries of Newton's third law are depicted in Table 8 which shows five components of the third law. In the table, an X indicates whether subjects mentioned this component in their summary. Three of four expert subjects (E1, E2, and E4) and

Table 8

Newton's Third Law Decomposed into Five Components and Two Sample Protocols

	N1	N2	N3	N4	E1	E2	E3	E4
Reaction opposite in direction	X	X	X	X	X	X	X	X
Reaction equal in magnitude	X		X	X	X	X	X	X
Action-Reaction involves two general bodies					X	X		X
Action-Reaction are general forces extended by each body on the other					X	X		X
Direction of Action-reaction is a straight line					X			

Examples of Subjects' Summary Protocol

N2 "And his third law states that for every action there's an opposite reaction to it."

E1 "The third law. . . states that for every action there is an equal and opposite reaction, or in other words, if Body A exerts a force on Body B, then Body B exerts a force on Body A in a direction which is along the line joining the two points. When you say bodies in this chapter, you mean they are really particles, point masses."

none of the novices emphasized the condition in which the law applies, that is, in situations where there are two bodies in interaction (row 3). In fact, the novices' discussions leave open the possibility that they would attempt to form action-reaction pairs on the same body.

To further support the idea that novices do seem to have well developed schemata of object concepts, we can compare inclined plane problem diagrams drawn by Novice H. P. and Expert M. G., whose network representations we show in Figures 5 and 6. In Figure 7 we can see no essential differences in the diagrams drawn by the expert and the novice.

From these partial analyses of our data, we can tentatively suggest that novices can have complete data structures (or well developed schemata) for object concepts, such an an inclined plane, a pulley, etc. Well-developed object concept schemata are probably sufficient to enable novices to solve simple problems correctly. What they lack are general relations between these object concepts and physics principles, which may be useful for solving more complex problems involving these objects.

Study Four: Feature Identification

It appears then that experts can elicit top-level principles from surface elements in the problem statement. The focus of the fourth study was to clarify the problem features that enable experts to

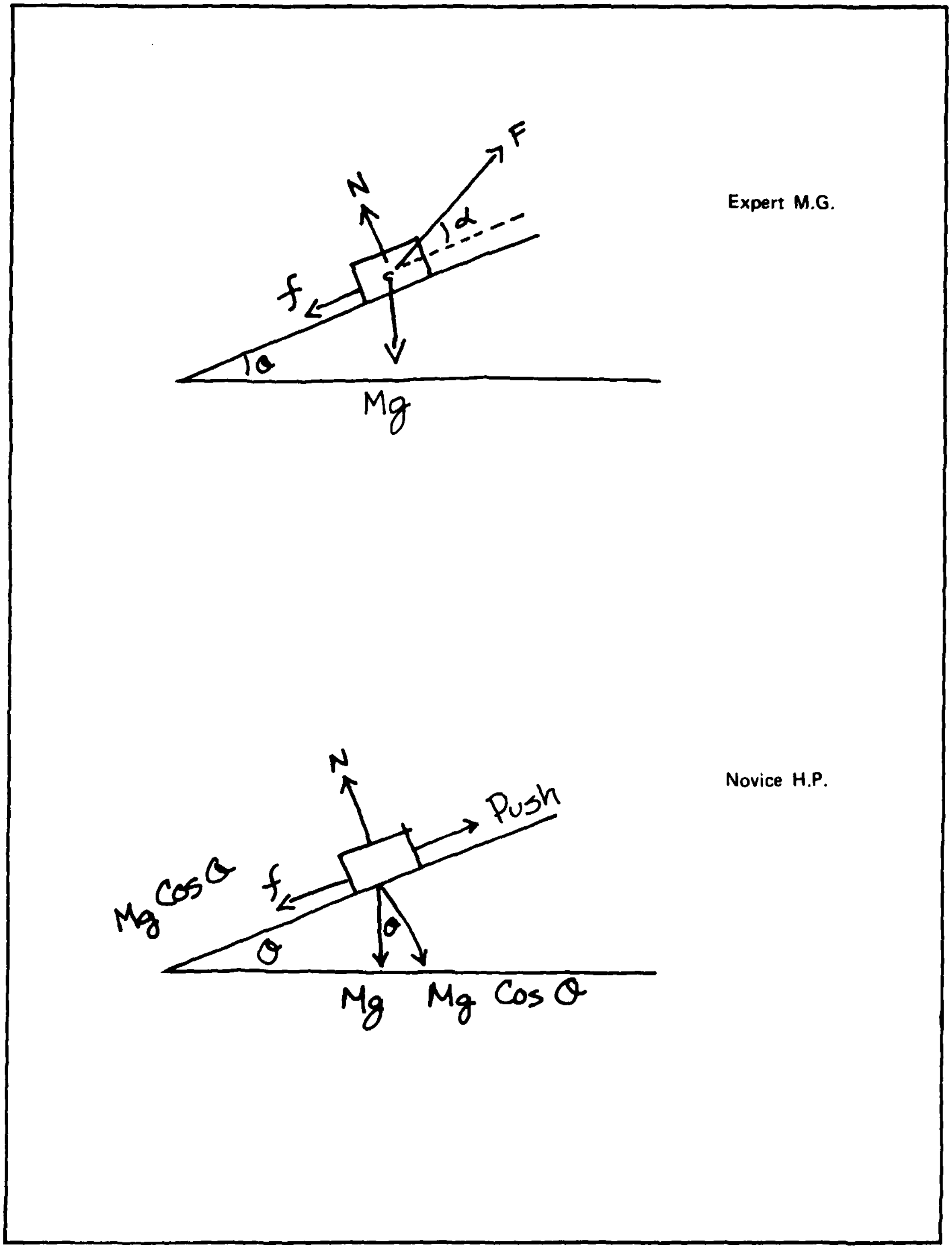


Figure 7. Diagrams drawn by an expert (M.G.) and a novice (H.P.) depicting an inclined plane problem.

elicit these principles. Subjects in this study were asked to read problem statements and to think out loud about the "basic approach" that they would take toward solving the problem. Subjects were encouraged to report all thoughts and hunches they had while deciding upon a "basic approach," even if these ideas occurred during the reading of the problem. Following this unconstrained thinking period for each problem, subjects were asked to state their "basic approach" explicitly and to state the problem features that led them to their choice.

The subjects were two physicists who had frequently taught introductory mechanics and two novices who had completed a basic college course in mechanics with an A grade. The problems used in this task were the same 20 (described in Table 3) used for the sorting replication (Study Two). That is, the problems crossed surface configurations with principles.

Analysis of Features. Table 9 gives the final "basic approaches" for all 20 problems for the two experts. Two aspects of these results are noteworthy. First, the responses given as "basic approaches" are the same kinds of descriptors other experts had given in the sorting tasks, i.e., the major principle they would apply to the problem. Secondly, intersubject agreement is nearly perfect. What looked superficially like disagreement between one subject's use of "work" and the other subject's use of "Conservation of Energy" (Problems 5 and 7) disappeared after postexperiment discussion.

Expert J.L. made a distinction between "energy" problems in which a dissipative force must be accounted for in the energy equation (work) and problems involving no dissipative force (strict Conservation of Energy). Expert V.V. made no overt distinction between these types, treating the "work" problems as a special case of Energy Conservation.

Results from the two novices were difficult to analyze because they had difficulty understanding and carrying out the task instructions. The novices found that they could not easily separate an abstracted plan for solution from the actual process of problem-solving: When asked to develop and state "a basic approach," they frequently attempted to solve the problem, giving the equation sets they would use. Their inability to abstract a solution plan indicates that their solution methods are closely bound to surface features.

We next examined the second portion of the protocols where subjects explicitly stated the features of the problems that led to their "basic approach." This analysis revealed several interesting aspects that are consistent with our interpretations from earlier experiments. Table 10 shows the frequency with which problem features were cited by the two experts and two novices as salient for leading to their "basic approach." A feature was included if it was mentioned (across 20 problems) at least twice by either of the two subjects, or once by both. The numbers given represent the number of problems for

Table 9

Final Stated "Basic Approaches" of Experts V. V. and J. L.

	V. V.	J. L.
Problem 1	Center of mass	Center of mass
Problem 2	Conservation of angular momentum	Conservation of angular momentum
Problem 3	F = MA	Dynamics: F = MA or work
Problem 4	Conservation of momentum	Conservation of momentum
Problem 5	Conservation of energy	Dynamics: work
Problem 6	Conservation of momentum and conservation of energy	Conservation of energy
Problem 7	Conservation of energy	Work and energy
Problem 8	F = MA	F = MA
Problem 9	Conservation of energy or F = MA (favored) (not sure)	Conservation of energy
Problem 10	Conservation of momentum and conservation of energy	Conservation of momentum and conservation of energy
Problem 11	F = MA	F = MA
Problem 12	F = MA	F = MA
Problem 13	Conservation of rotational momentum	Conservation of rotational momentum (changed mind from conservation of energy)
Problem 14	F = MA	F = MA
Problem 15	F = MA	Pseudo F = MA
Problem 16	Conservation of energy	Conservation of energy
Problem 17	Conservation of momentum and conservation of energy	Conservation of momentum and conservation of energy
Problem 18	Newton's Third	Newton's Third
Problem 19	Conservation of energy	Conservation of energy
Problem 20	Conservation of energy	Conservation of energy

which each subject listed each feature as influential in his or her "basic approach" decision.

First of all, as can be seen in the table, the kinds of features mentioned as relevant by the novices are different from those identified as relevant by the experts. There is essentially no overlap in the features selected by novices and experts except for the object "spring." Relevant features selected by the novices are again literal objects and entities that can be identified in the problem statement, such as "friction," "gravity," etc. Features identified by the experts can be characterized as descriptions of the states and conditions of the physical situation described by the problem. In some instances, these are transformed or derived features, such as a "before and after situation" or "no external forces." Because these features are not explicitly stated in the problem, that is, the referents in the problem are not obvious, we refer to these features as second-order features. Second-order features are almost never mentioned by the novices.

Since second-order features must necessarily be derived from more literal surface features that are in the problem statements, it is of interest to see if the surface features in the problem statement that elicit these second-order features can be identified. In order to do this, we can examine the initial part of the protocols where second-order features were mentioned, and infer the literal surface features from which these were elicited. Such inferences can be made

Table 10

Key Features Cited by Experts and Novices

	Experts	
	V. V.	J. L.
Given initial conditions	9	3
Before and after situations	3	4
Spring	0	5
No external force	4	1
Don't need details of motion	4	1
Given final conditions	5	0
Asked something at an instant in time	4	1
Asked some characteristics of final condition	4	0
Interacting objects	0	4
Speed – distance relation	0	4
Inelastic collision	2	2
No initial conditions	4	0
No final conditions	4	0
Energy easy to calculate at two points	1	2
No friction or dissipation	3	1
Force too complicated	0	3
Momentum easy to calculate at two points	2	1
Compare initial and final conditions	2	0
Can compute work done by external force	2	0
Given distance	1	1
Rotational component	0	2
Energy yields direct relation	0	2
No before and after	2	0
Asked about force	2	0

	Novices	
	P. D.	J. W.
Friction	3	5
Gravity	3	3
Pulley	3	3
Inclined plane	3	2
Spring	2	3
Given masses	3	2
Coin on turntable	1	1
Given forces	1	1
Force – velocity relation	0	2

more easily from protocols in which subjects gave responses after reading segments of the problem statement. In such cases, we can make mappings between what was read and what was said. In any case, such inferences are difficult and must be speculative.

Table 11 categorizes the "basic approaches" given by Expert V.V. into three main principles shown in column 1. Column 2 lists second-order features he often identified as helpful in deciding on a "basic approach." Column 3 gives examples of "surface" information from problem statements that we infer contributed to Expert V.V.'s second-order features. For example, it appears that Expert V.V. judges a problem to be a Conservation of Momentum problem when it involves a "before and after" situation with "no external forces or torques." "Before and after" situations, in turn, are identified in a problem when it has either a physical process with end points (e.g., something starts and eventually stops) or a physical state that changes abruptly (e.g., there is a point where the girl has the rock and a point after which she does not). "No external forces" can sometimes be directly derived from the problem given, such as "neglecting friction" or may involve complex inference on the subject's part. It is clear that for the expert, even "first-order" features that feed second-order features can themselves be complex information configurations.

Perhaps the most important difference between the expert's and novice's selection of problem features is that even though, in some

Table 11

The First- and Second- Order Features that Elicited Expert V. V.'s Final "Basic Approach"

Principles	Second-Order Features (Derived Features)	First-Order Features (Surface Features)
Conservation of Momentum (Problems 2, 4, 13)	Before and after situation	Girl on *still* merry-go-round *throws* a rock. . . . Two initially separated wheels are *suddenly coupled.*
	No external forces	Neglecting friction. No third entity mentioned except the interacting wheels.
Conservation of energy (Problems 5, 7, 16, 19, 20)	Before and after situation	Block *dropped* from a height X *onto* a spring. Block *starts* with initial velocity V. How *far* will it slide?
	Given or well defined initial conditions	Initial height = X. Initial velocity = 0. Initial velocity = V.
Force Laws (Problems 3, 8, 9, 11, 12, 14, 15)	Determination of something at an instant in time.	Break point of a rope. Coin observed to slide at distance R from center of turntable. Raising point of a disk.

sense, both the expert and the novice use features based on words in the problem statement, the expert sees the abstracted and/or transformed features as the relevant features. The novice appears to lack the necessary abstraction or transformation of the literal features into higher level features. The features identified by the novices (Table 10) are nondiscriminating from the point of view of the expert, i.e., the expert at times applies various physics laws across problems involving the various features (e.g., "springs," "incline") cited by the novices; thus indicating characteristically different "basic approaches" for experts and novices.

A schematic representation of the hierarchical nature of the structure of physics knowledge, especially for the expert, is sketched in Figure 8. This figure indicates how surface knowledge, such as "words" in a problem statement, can sometimes elicit intermediate knowledge states (an implied physical condition such as "no external forces") which can in turn elicit principles, and, at other times, surface knowledge can elicit principles directly. Hence, processing for the experts can be bottom-up, from words to intermediate knowledge states to principles, or top-down: That is, not only can the words elicit the basic principles, but the principles can also generate intermediate knowledge states and objects and entities in a potential problem. For example, in Study Three, when Expert M.G. elaborated on a separate concept term, the principle of "Conservation of Energy," she defined and explicated the inclined plane schema as one instance of a Conservation of Energy problem. Novices, on the other hand, generally did not exhibit an organization of knowledge that permits this hierarchical accessibility.

To summarize this portion of our analyses of problem features, the following differences in feature identification should be reiterated. First, the expert's selection of features relevant to problem-solution are derived from more fundamental "surface" features, whereas the novice cites only literal concepts in the problem statement (see Table 10). Second, literal features, which may have been used by the expert to derive the second-order features, appear to involve larger units of information than those used by the novice (compare column 3 of Table 11 with the features identified as relevant by the novices in Table 10). Finally, we hypothesize that the transformation of one level of features to the other can occur in both directions for the expert: Principles can generate potential problem configurations and physical conditions, and literal surface features can be abstracted into deeper physical conditions and/or principles.

Analysis of the Process of Arriving at a "Basic Approach". Another aspect of the protocol data of this fourth study that gives interesting insight into knowledge structure and problem solving is the process by which a subject arrives at a "basic approach," or, for the novice, it is better thought of as the procedure used to arrive at a solution. Typically, upon immediate presentation of a problem, the expert entertains a hypothesis (a potential physics principle) or a set of competing hypotheses. (Expert J.L. generated her first

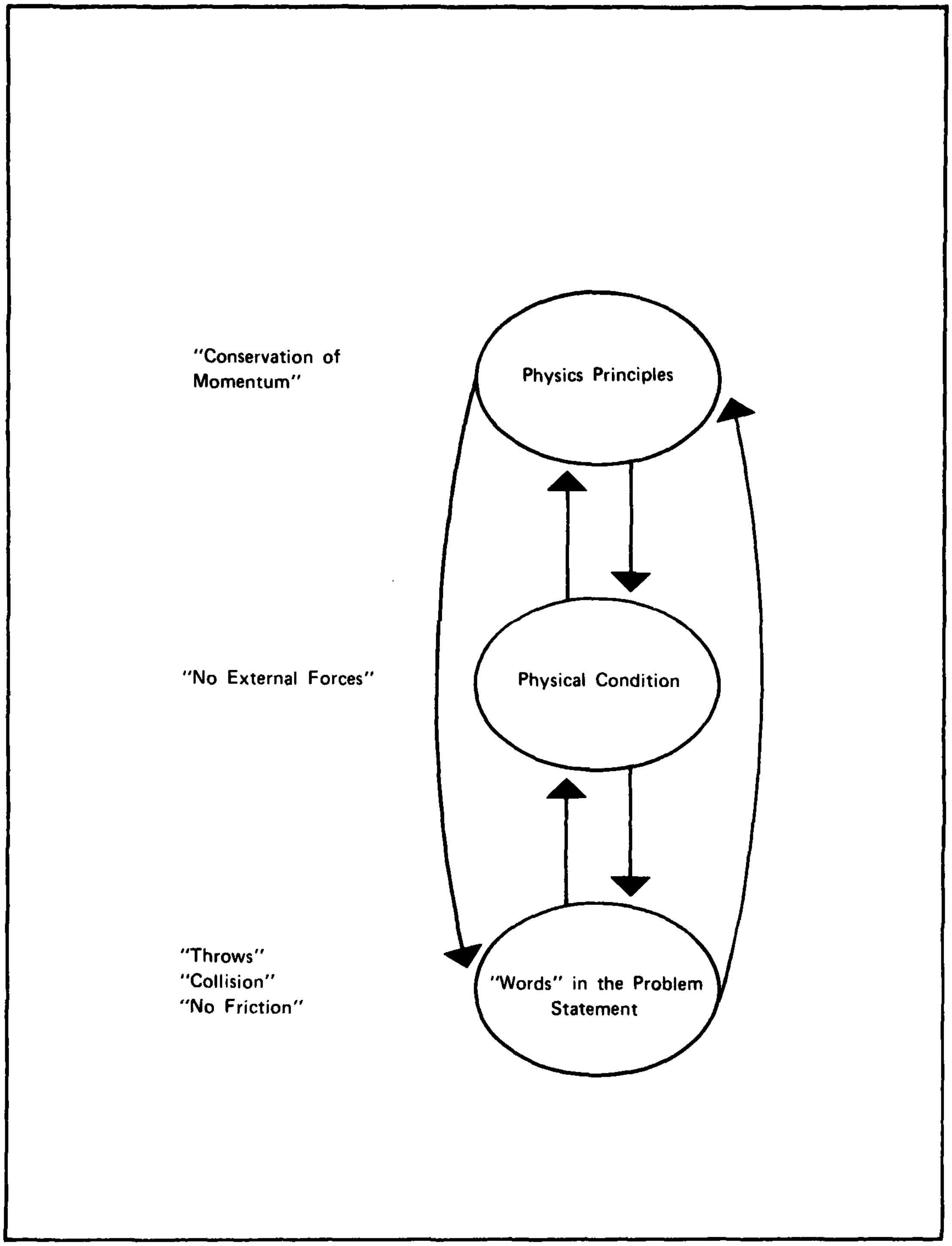


Figure 8. Hierarchical structure of physics knowledge.

principle(s) after reading 20% of the problems on the average.) This is followed by the introduction of additional features, which are used to confirm, reject, or choose among hypothesized principles.

A process of this kind is shown in Figure 9, which gives a schematic analysis of Expert J.L.'s development of a "basic approach" for Problem 16. Problem segments (column 1) and protocol segments (column 4) represent actual subject break points in the reading of the problem; that is, after having read the phrase A block of mass M is dropped from a height X, Expert J.L. paused and uttered the protocol indicated in column 4. Columns 2 and 3 represent our analysis of the possible second-order features and principles that the subject is deriving from that particular segment of the problem. Our interpretation is based on both the contents of her protocol at that point in time, as well as her comments during the later probing section of the interview when she explicitly mentioned the actual features (see Table 10) that led her to a final "basic approach." Hence, we are hypothesizing that, following initial encoding of problem features which may be transformed into second-order features, the hypothesis "Conservation of Energy" is generated. This is followed by prediction and continuing analysis of problem features that are required for establishing the principle as Conservation of Energy. As other first- and second-order problem features are confirmed, the hypothesized principle is maintained. Final consideration of the feature "maximum spring compression" completes the requirement for a "before and after" second-order feature, which in turn, along with "no dissipative forces," hierarchically completes and confirms the Conservation of Energy schema.

The solution process of a novice (P.D.) for the same problem is given in Figure 10. Because the subject gave no protocol before reading the entire problem, we created hypothetical problem segments (column 1) based upon our interpretation of his protocol. Column 2 is comprised of equations that can be derived from his protocol in column 3. In this example, we presume that the idea of falling as indicated by A block of mass M dropped from a height X elicits the idea of gravity which, with the addition of a mass, generates the equation F=Mg. The "spring" and the "spring constant" suggests the equation F=-kx. Following the generation of these two separate and parallel knowledge states, the novice sees a common element between them which is "F", the forces. This enables him to equate the two, thereby eliminating the unknown. The novice in this case solves the problem by generating equations that are directly related to the entities in the problem statement, then seeks relationships in the algebraic expressions to eliminate unknowns. Such an approach is simple and straightforward, and can lead to successful solutions, although in this particular case the solution method was wrong.

The solution method of this novice is not unlike the problem solving processes described by Simon and Simon (1978) as "working backward" since the immediate goal of the novice is to find a solution

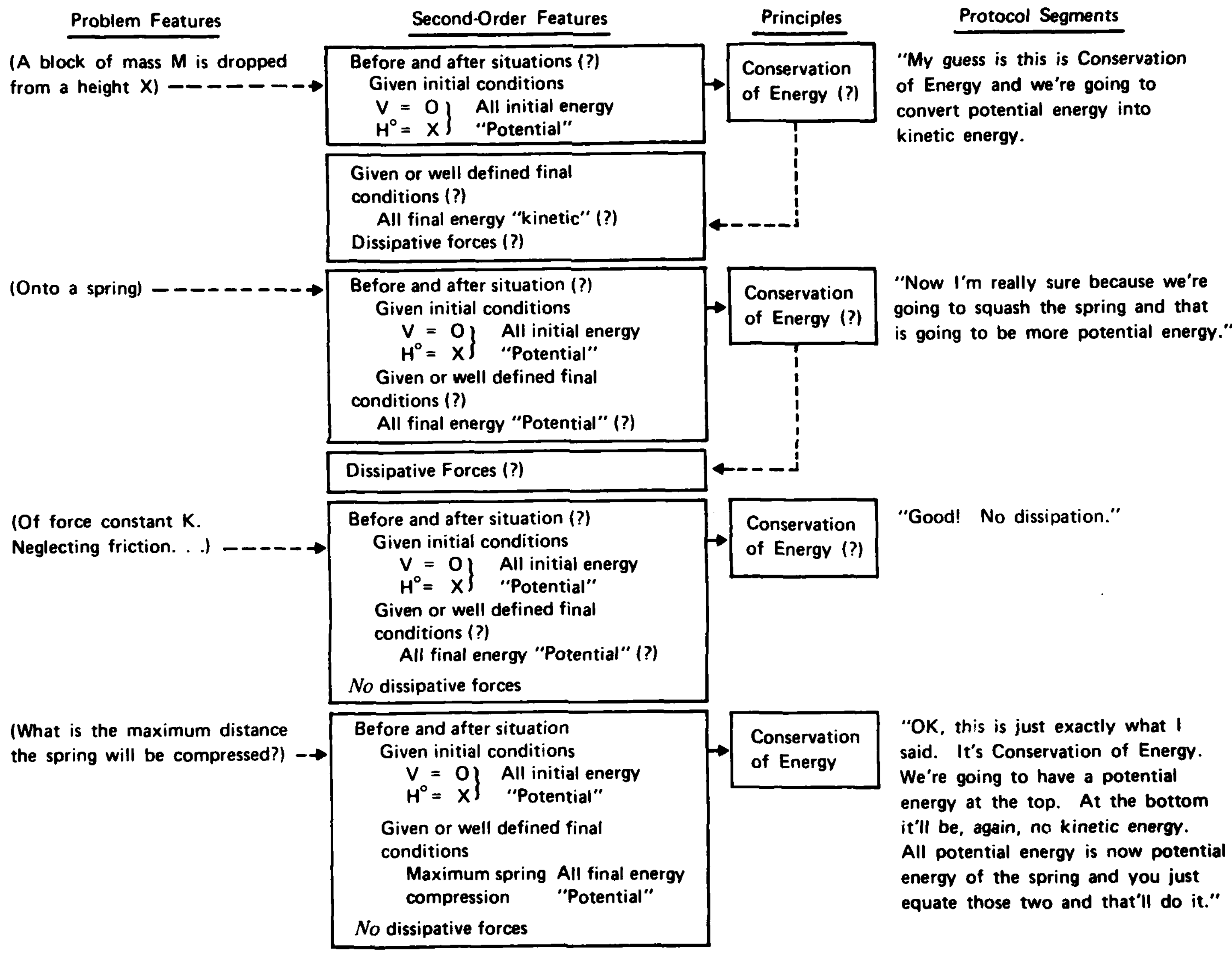


Figure 9. An example of Expert J.L.'s development of a "basic approach" during reading of a problem. "?" indicates hypotheses yet to be confirmed.

Problem Features	Equations	Protocol
(A block of mass M is dropped from a height X.) ↓	$F = Mg$	"Okay. If it's dropped from. . .mass M from height X, it's a mass M from height X. You would figure out the force you get from that, and that's mass times acceleration. You figure out the force it requires, and then finding the force, you know that the K is the force constant and X is the amount of compression and that would be equal to the force that it hits with. So then you'd just solve backwards for X. Find the amount of force that mass hits the spring with and just use that in relating that the force is equal to −kx and X is what we're trying to find. Well not height X, amount of compression X."
(onto a spring of force constant K) ↓	$F = Mg$ $F = -kx$	
(Neglecting frinction, what is the maximum distance the spring will be compressed?)	$Mg = -kx\ max$	

Figure 10. An example of Novice P.D.'s development of a "basic approach" after reading of a problem.

for the unknown quantity often given by the problem question. This example accentuates the novice's direct reliance on equations and algebraic manipulations, which we have also found elsewhere (Fogarty & Chi, 1980).

In summary, the two kinds of analyses carried out in this study--the identification of features and the description of the processes leading to a potential solution--enable us to propose an explanation for a general difference in expert and novice problem solving found in our work and elsewhere (Simon & Simon, 1978). A prominent finding in the literature is that during the solving of a physics problem, the ordering in the sequence of equations generated by a novice can be characterized as a "backward-working" strategy, where the explicitly stated unknown of the problem initiates the preliminary set of equations. *Additional* equations are added, and the set manipulated algebraically for the unknown. We speculate that this method of solution occurs because, for the novice, problem solving involves the generation of a series of equations associated with specific literal objects and entities in the problem statement. Since the unknown (such as "find the velocity") is often stated literally, an equation containing the unknown is usually among the first equations elicited.

Problem solving for the expert, on the other hand, has been characterized as having two distinct phases. First, the expert engages in an elaborate qualitative analysis of the problem prior to working with the appropriate equations. Second, the ordering of the generated equations resembles more a "forward-working" strategy, where the initial equations generated contain not the unknown of the problem, but the known values. The manipulation of these equations and subsequent generation of additional equations eventually yields the desired unknown. We speculate that this method of solution for the expert occurs because the early phase of problem solving for the expert (the qualitative analysis) involves the activation and confirmation of an appropriate principle-oriented schema. The initial activation of this schema can occur as a data-driven response to some fragmentary cue in the problem. Once activated, the schema itself specifies further (schema-driven) tests for its appropiateness (Bobrow & Norman, 1975). When the schema is confirmed, that is, the expert has decided that a particular principle is appropriate, the principle provides the general form that specific equations to be used for solution will take. For example, once the problem solver has decided to use an energy conservation approach, the general form of the solution equation involves energy terms equated at two points. The solver then needs only to specify these terms for the problem at hand. This would account for the forward-working character of the expert in that the equations used depend more on the way the problem is represented than on the "unknown." While the problem unknown obviously cannot be ignored by the expert, the status of the unknown in the expert solution method appears secondary to that of deciding which physics principles have their conditons of applicability met in the problem. Hence, analogous to the way that a chess expert's initial classification yields a small set of "good" alternative moves, which must then be investigated analytically (Chase & Simon, 1973), the physics expert's initial categorization restricts search for a particular solution to a small range of althernative variations on a general theme.

Summary

The exploratory studies reported here derive from the assumption that problem solving in a rich domain begins with the construction of an initial representation that is a function of an individual's level of expertise, and that the properties of this representation guide subsequent problem-solving processes. While most earlier studies have analyzed this subsequent search and solution process, the present work attempts to understand the nature of initial problem representation.

In a first study where subjects sorted physics problems into categories, the categories generated by experts were characteristically different than the categories generated by novices. The groupings of the novices reflected the surface structures of problems; such surface features included objects referred to in the problem, untransformed physics terms mentioned, or given visual representations or diagrams. In contrast, problem categorization by experts was based on a transformation of the surface features of the problems into appropriate underlying physics laws. Apparently, both experts and novices have well-formed schemata of problem types, but they are not the same.

A second study of problem categorization employed an especially designed set of problems in which surface features intersected with applicable physics laws. As anticipated, the novice's classification was based on the surface structures of the problem and excluded consideration of the physics principles involved. The expert used a smaller number of problem categories based upon three underlying physics laws in the given problem set. Of particular interest was the finding that the groupings of an individual of intermediate competence fell between the novice and the expert. This advanced novice generated categories in which physics principles were constrained by the surface components included in a problem.

The results of the first two studies imply that the attainment of expertise in physics problem solving involves the following levels of learning: For the novice, the initial representation stage of problem solution is closely tied to the surface level appearance of problems; as basic physics principles are incorporated into the knowledge structure, the more general solution schema they employ are still bound to particular surface features. With the increasing attainment of expertise, there is a gradual release from sole dependence on literal physical features, and higher-level problem representation is acquired that consists of an abstraction or transformation of problem features that generalizes across surface forms.

In a third study, experts and novices were asked to elaborate on prototypical concepts used by subjects in describing their classifications in the sorting studies. In the protocols obtained, the novice's schema for surface features of the problem were well developed and contained numerous variables to be instantiated. The expert's protocol was similar in this respect, but different in that immediate mention was made of alternative physics principles that could be applicable for problems containing similar surface features. An interesting expert-novice distinction that appeared was that in addition to physics principles, and in contrast to the novice, the expert considered the conditions under which different principles could be applied. Thus, the expert appeared to have associated with the basic principles appropriate procedural knowledge about their applicability.

A fourth study focused upon clarification of problem features that enabled experts and novices to elicit their initial representations--particular problem features that led to decisions about their basic approach to or plan for problem solution. The task of this experiment was more difficult for novices than for experts; apparently, novices found it difficult to separate an abstracted plan for solution from the process of solving the problem. When asked to develop and state a basic approach, they proceeded to try to actually solve the problem, giving the equation sets they would use. While both experts and novices used the words and diagrams in a problem statement, the experts abstracted or transformed features as relevant for problem solution. The novice does not transform the literal features into higher level features and those features defined by the novices were nondiscriminating from the point of view of the expert. The novice appears to be very dependent on the literal features of the problem. The expert, in contrast, appears to have a flexibility whereby the transformation of problem features can occur in both a top-down or bottom-up fashion. That is, principles can generate potential problem configurations and physical conditions and literal surface features can be abstracted into deeper physical principles and applicable conditions.

The findings of these exploratory studies offer an explanation of a general difference in expert and novice problem-solving processes found elsewhere in the literature. The finding is that novices tend to use strategies of equation manipulation directed by the explicitly given goals of a problem. Experts, in contrast, start with elaborate qualitative analyses prior to working with appropriate equations. Problem solving for the novice involves the generation of a series of specific equations associated with surface feature entities, and solution of a problem involves manipulation of these equations until the desired unknown is achieved. Problem solving for the expert begins with the activation of principle oriented schema, and these high-level schema provide a global plan that subsequently constrains the form of a particular solution process. In this sense, the expert's initial categorization restricts the search for a particular solution. Followup studies of particular importance that need to be carried out should investigate the interaction between subsequent solution processes and the properties of initial representation. Of particular significance in the study of the learning process involved in attaining expertise is understanding how the flexibility to move between higher and lower levels of knowledge structure is acquired.

Acknowledgment

This research program, conducted at the Learning Research and Development Center, is supported in part by contract No. N00014-78-C-0375, NR 157-421 of the Office of Naval Research, and in part by the National Institute of Education. A portion of this paper was presented at the annual meeting of the Psychonomic Society, Phoenix, November 1979. The authors are grateful for the help of Christopher Roth and Andy Judkis for comments, data collection, and analysis. Reprint requests should be sent to the first author, at the Learning Research and Development Center, University of Pittsburgh, Pittsburgh, PA 15260.

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Footnotes

[1]For example, if a subject said of a problem group: "These all involve inclined planes, some with a frictional surface, some frictionless," the label "inclined planes" was counted since it applied to all problems in the set. Examples such as this, indicating possible subdivisions within categories, have suggested the need for an augmented sorting methodology in which subjects are encouraged to make further discriminations within initial categories and are allowed to aggregate initial categories into higher-order groups. We are currently conducting such studies.

[2]The problems were chosen or constructed and the a priori classification scheme created by Andrew Judkis, an assistant in the project who is a senior electrical engineering major with substantial experience in physics. It was clear that some problems could be solved using approaches based on either of two principles, Force and Energy, and in fact Andrew solved them both ways. In these cases, the problem is listed under the principle he judged to yield the simplest or most elegant solution but is marked with a cross. Also, some problems were two-step problems involving both momentum and energy. These are listed under the principle that seemed most important (in this case, momentum conservation) and are marked with a "+". These two-step problems are not designated explicitly as involving two principles. Some problems involve more than one potential physical configuration, e.g., "a pulley attached to an incline." These are

marked with a single asterick and listed multiply under alternative features.

[3]Some support for this claim derives from the fact that just about every novice we have ever run in our studies has had a small number of problems he or she sees as involving physics laws. For example, "Bullet into Blocks," a classic teaching situation for Conservation of Momentum, is generally seen as a momentum problem. The point, however, is that it may be the only problem in the problem set thus seen.

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