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ABSTRACT

This paper briefly reviews research on tasks in knowledge-rich domains including developmental studies, work in artificial intelligence, studies of expert/novice problem solving, and information processing analysis of aptitude test tasks that have provided increased understanding of the nature of expertise. Particularly evident is the finding that expertise is acquired when people continually try to confront new situations in terms of what they know. Increasing ability to solve problems and generate new information is fostered by available knowledge that can be modified and restructured. Initial knowledge structures, when they are interrogated, instantiated, or falsified by novices in the course of learning and experience lead to organizations of knowledge that are the basis for the more complete schemata of experts. Acquiring expertise is seen as the successive development of procedurally oriented knowledge structures that facilitate the processes of expertise. A set of propositions is listed that summarizes conclusions from research as well as broader inferences and speculations. (PN)

University of Pittsburgh

LEARNING RESEARCH AND DEVELOPMENT CENTER

THOUGHTS ON EXPERTISE

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Research on tasks in knowledge-rich domains including developmental studies, work in artificial intelligence, studies of expert/novice problem solving, and information-processing analyses of aptitude test tasks have provided increased understanding of the nature of expertise. Particularly evident is the finding that structures of organized knowledge enable the cognitive processes characteristic of high levels of competence. This paper briefly reviews this research and lists a set of propositions that summarize conclusions from research as well as broader inferences and speculations.

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Thoughts on Expertise

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General Remarks

Introduction

Information-processing studies of problem solving in the 1960s and 1970s accepted the tradition of early experimental psychology in concentrating primarily on the study of "knowledge-lean" tasks in which competence can usually be acquired over short periods of learning and experience. Studies of these tasks illuminated the basic information-processing capabilities people employ when they behave more and less intelligently in situations where they lack any specialized knowledge and skill. The pioneering work of Newell and Simon and others richly described general heuristic processes (such as means-end analysis, generate and test, and subgoal decomposition), but provided limited insight about the learning and thinking that require a rich structure of domain-specific knowledge.

In contrast to this, in more recent years, work has examined knowledge-rich tasks that require hundreds and thousands of hours of learning and experience in an area of study. Studies of expertise have attempted to sharpen this focus by describing contrasts between the performance of novices and experts. And the novices in these studies, e.g., intern radiologists, electronics technicians, etc., have engaged in learning over much longer periods than are required for short experimental tasks.

Investigations of problem solving in knowledge-rich domains show strong interactions between structures of knowledge and cognitive processes. The results force us to think about high levels of competence in terms of the interplay between knowledge structure and processing abilities. The data illuminate a critical difference between individuals who display more and less ability in particular domains of knowledge and skill, namely, the possession of rapid access to and efficient utilization of an organized body of conceptual and procedural knowledge.

Data and theory in developmental psychology, studies of expert/novice problem solving, and process analyses of high and low scorers on intelligence and aptitude test tasks show that a major component of expertise is seen to be the possession of this accessible and usable knowledge.

Developmental Studies

As a warming up exercise (and to introduce a point of view), let me briefly mention some developmental studies with children. Chi, in several studies (Chi, 1978; Chi & Koeske, 1983), examined recall in children. She contrasted high- and low-knowledge children in chess skill and also children with high and low knowledge of dinosaur categories and features. Her results replicated in significant ways the early chess studies of DeGroot (1965), and of Chase and Simon (1973a, 1973b); high-knowledge subjects showed better memory and encoding performance than low-knowledge individuals. And this superiority was attributed to the influence of knowledge in content areas rather than to the exercise of memory capabilities as such. Changes in the knowledge base appear to enable sophisticated cognitive performance.

Susan Carey's studies of animistic thinking in young children (in press), trace the emergence of a child's concept of "alive." She documents a change, something like an expert/novice shift, from a knowledge organization centering around human characteristics (a novice point of view) to a knowledge organization centering around the biological functions of living things. Carey makes the point that what can be interpreted as abstract pervasive changes in a child's reasoning and learning abilities come about as knowledge is gained in a given domain.

The acquisition of content knowledge as a factor in acquiring increasingly sophisticated problem-solving abilities is pointed to in Siegler and Richards's "rule assessment" studies (1982). They conclude that "knowledge of specific content domains is a crucial dimension of development in its own right and that changes in such knowledge may underlie other changes previously attributed to the growth of capacities and strategies" (p. 930).

Artificial Intelligence

A focus on the structure of knowledge is also apparent in AI systems. In contrast to earlier emphases on general problem-solving techniques to guide a search for any problem--a power-based strategy--Minsky and Papert (1974) emphasize the role of a knowledge-base emphasis in achieving intelligent thinking. They write:

> The *Power* strategy seeks a generalized increase in computational power . . . it may look toward extensions of deductive generality, or information retrieval, or search algorithms. . . . In each case the improvement sought is . . . independent of the particular data base.
>
> The *Knowledge* strategy sees progress as coming from better ways to express, recognize, and use diverse and particular forms of knowledge. . . . It is by no means obvious that very smart people are that way directly because of the superior power of their general methods--as compared with average people. . . . A very intelligent person might be that way because of specific local features of his knowledge-organizing knowledge rather than because of global qualities of his "thinking." (p. 59)

Expert/Novice Problem Solving

The work on problem solving in adult experts and novices has shown fairly consistent findings in quite a variety of domains--chess play, physics problem solving, the performance of architects and electronic technicians, and skilled radiologists interpreting x-rays. (I mention general conclusions only here but will provide more specific information in a final list of propositions about expertise.) This work has shown that relations between the structure of a knowledge base and problem-solving processes are mediated through the quality of representation of the problem. This problem representation is constructed by the solver on the basis of domain-related knowledge and the organization of this knowledge. The nature of this organization determines the quality, completeness, and coherence of the internal representation, which in turn determines the efficiency of further thinking.

Expert/novice research suggests that novices' representations are organized around the literal objects and events given explicitly in a problem statement. Experts' knowledge, on the other hand, is organized around inferences about principles and abstractions that subsume these factors. These principles are not apparent in the statement or the surface presentation of the problem. For example, in our studies with mechanics problems, novices classify problems on a surface level, according to the physical properties of a situation--a spring problem or an inclined plane problem. Experts categorize problems at a higher level, in terms of applicable physics principles--a Newton's second law problem, a conservation of energy problem.

In addition, experts know about the application of their knowledge. Their declarative information is tightly bound to conditions and procedures for its use. An intermediate novice may have sufficient knowledge about a problem situation, but lack knowledge of conditions of applicability of this knowledge.

Consider a somewhat technical example. From protocols of novices and experts in solving elementary physics problems, we attempted to define the structure of their knowledge in the form of node-link networks (Chi, Glaser, & Rees, 1982). The nodes are key terms and physics concepts mentioned by the subjects. The links are unlabeled relations that join the concepts mentioned contiguously in the solver's protocol. The network of a novice's (H.P.) and an expert's (M.G.) elaboration of the concepts of an "inclined plane" problem are shown in Figure 1 and 2 respectively. We can view each of these concepts as representing a potential schema; the terms and concepts mentioned in the protocol can be thought of as the variables (slots) of the schema. For example, in Novice H.P.'s protocol, his inclined plane schema contains numerous variables that can be instantiated, including the angle at which the plane is inclined with respect to the horizontal, whether a block is resting on the 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, the coefficients of static and kinetic friction. The novice also discusses possible forces that may act on the block, for example, the drag of a pulley. He also discusses the pertinence of Conservation of Energy, but this was not elicited as a part of a solution procedure applicable to a configuration involving an inclined plane, as is the case with the expert. Hence, in general, one could say that the inclined plane schema that the novice possesses is quite rich. He knows precisely what variables ought to be specified, and he also has default values for some of them. For example, if friction was not mentioned, he probably knows that he should ignore friction. Hence, with a simple specification that the problem is one involving an inclined plane, he can deduce fairly accurately what the key components and entities are (i.e., friction) that such a problem would entail.

However, the casual reference to the underlying physics principle, Conservation of Energy, given by the novice contrasts markedly with the expert's protocol (Fig. 2). She immediately makes a call to two principles that take the status of procedures, the Conservation of Energy Principle and the Force Law. (In Greeno & Riley's, 1981, terminology, they would be considered calls to action schemata.) We characterize them as procedures (thus differentiating them from the way the novice mentioned a principle) because the expert, after mentioning the Force Law, continues to elaborate the condition of applicability of the procedure and then provides formulas for two of the conditions (enclosed in dashed rectangles in Fig. 2). After her elaboration of the principles and the conditions of applicability of one principle to inclined plane problems (depicted in the top half of Fig. 2), Expert M.G. continued her protocol with descriptions of the structural or surface features of inclined plane problems, much like the descriptions provided by Novice H.P. Hence, it seems that the knowledge common to subjects of both skill groups pertains to the physical configuration and its properties, but that the expert has additional knowledge relevant to the solution procedures based on major physics laws.

Another way of viewing the difference between the novice's and expert's elaborations of inclined plane is to look at Rumelhart's description (1981) of schemata of inactive objects. Here an inclined plane is seen by the novice as an inactive object, so that it evokes not actions or event sequences but spatial relationships and descriptions of the configuration and its properties. Experts, on the other hand, view an inclined plane in the context of potential solution procedures, that is not as an object but more as an entity that may serve a particular function.

As in the developmental studies, the problem-solving "difficulties" of novices can be attributed largely to the nature of their knowledge bases, and much less to the limitations of their processing capabilities, such as their inability to use general problem-solving heuristics. Novices do show effective use of heuristics; the limitations of their thinking derive from their inability to infer further knowledge from the literal cues in a problem situation. These inferences are necessarily generated in the context of a knowledge structure that experts have acquired.

In general, study of problem solving by highly competent people in rich knowledge domains provides a glimpse of the power of human thinking to use a large knowledge system in an efficient and automatic manner--particularly in ways that minimize reliance on the search heuristics identified in studies of knowledge-lean problems. Thus, a significant focus for understanding expertise is identifying the characteristics and influence of organized knowledge structures that are acquired over long periods of time.

Aptitude Test Performance

Consider another converging area: process analyses of aptitude and intelligence test tasks performed by high- and low-scoring individuals. The evidence in this area comes from studies carried out by Earl Hunt and his colleagues (Hunt, 1978; Hunt, Frost, & Lunneborg, 1973), Robert Sternberg (1977b), and Pellegrino and Glaser (1982). My interpretation of several components of performance that differentiate high- and low-scoring individuals is the following: One component appears to involve rapid access to and management of working memory. The next two components appear to involve specific knowledge. The first is conceptual knowledge of the item content. Low-scoring individuals with less available knowledge encode at surface feature levels rather than at levels of generalizable concepts; this limits their inferential ability. The second component is knowledge of the solution procedures required for solving a particular task form, such as analogical reasoning or induction items. Low-scoring individuals display a weak knowledge of procedural constraints that results in procedural bugs, and an inability to recover the goals of an analogy problem when they need to pursue subgoals of the task. This weak knowledge of procedural constraints sometimes allows them to turn a problem into an easier one to solve, such as a word association task. Such acquired knowledge, then, is suggested as a significant aspect of skillful aptitude test performance.

Schemata and Theories

The organizations of knowledge that are developed by experts can be thought of in terms of schemata or theories of knowledge. I define a schema here as a modifiable information structure that represents generic structures of concepts stored in memory. Schemata represent knowledge that we experience, i.e., interrelationships between objects, situations and events that occur. In this sense, schemata are prototypes in memory of frequently experienced situations that individuals use to integrate and interpret instances of related knowledge. Schema theory assumes that there are schemata for recurrent situations, and that these schemata enable people to construct interpretations, representations, and perceptions of situations.

If we think of a schema as a theory or internal model that is used, matched, and tested by individuals to instantiate the situations they encounter, like a scientific theory, it is a source of representation and prediction. It enables individuals to impute meaning to a situation and to make inferences from information. As is the case for a scientific theory, if it fails to account for certain aspects of one's observations, it leads to learning that can modify or replace the theory. As a representation of a problem situation, it is accompanied by rules for solution of the problem.

Self-Regulation and General Skills

To temper my emphasis on structures of knowledge, I now point out that experts in various domains show self-regulatory or metacognitive capabilities that are not present in less mature or experienced learners. These abilities include knowing what one knows and doesn't know, planning ahead, efficiently apportioning one's time and attentional resources, and monitoring and editing one's efforts to solve a problem. To a large extent, I suspect that these self-regulatory activities are specific to a domain of knowledge in experts. Where they appear to be generalized competencies, i.e., in "generally intelligent" individuals, my hypothesis is that they become abstracted strategies after individuals use them in several fields of knowledge.

Perhaps widely competent children and adults, because of intensive exposure to different domains, employ skills that evolve as generalized cognitive processes. As general methods, however, these may be a small part of the intelligent performance shown by experts in specific fields of knowledge where they rapidly access acquired schemata and procedures. General processes may be important when an individual is confronted with problems in unfamiliar areas. However, future research may show that generalizable and transferable expertise lies in an ability to use familiar domains of knowledge for analogical and metaphorical thinking about new domains.

Generalizations

(1). There seems to be a continuous development of competence, as experience in a field accumulates. Eventual declines in competence may be the result of factors in the conditions of experience. Competence may be limited by the environment in which it is exercised. People may attain a level of competence only insofar as it is necessary to carry out the activities or to solve problems at the given level of complexity presented. Situations that extend competence may be less forthcoming as experts settle into their working situations.

(2). Expertise seems to be very specific. Expertise in one domain is no guarantee of expertise in other areas. It may be, however, that certain task domains are more generalizable than others, so that adults who are experts in applied mathematics or aesthetic design, or children when they learn measurement and number concepts, have forms of transferable expertise.

(3). Experts develop the ability to perceive large meaningful patterns. These patterns are seen in the course of their everyday activities. This pattern recognition occurs so rapidly that they take on the character of the "intuitions." In contrast, the patterns novices recognize are smaller, less articulated, more literal and surface oriented, and much less related to inferences and abstracted principles. The extraordinary representational ability of experts appears to depend on the nature and organization of knowledge existing in memory. As I indicated earlier, the fact that an expert has a more coherent, complete, functional and principled representation of knowledge than a novice necessarily implies an initial understanding of a problem that leads more easily to correct procedures and solutions.

(4). The knowledge of experts is highly procedural. Concepts are bound to procedures for their application, and to conditions under which these procedures are useful. The functional knowledge of experts is related strongly to their knowledge of the goal structure of a problem. Experts and novices may be equally competent at recalling small specific items of domain-related information. But high-knowledge individuals are much better at relating these events in cause-and-effect sequences that relate to the goal and subgoals of problem solution.

(5). These components of expertise enable fast-access pattern recognition and representational capability that facilitate problem perception in a way that greatly reduces the role of memory search and general processing. Novices, on the other hand, display a good deal of search and processing of a general nature. Their perceptions are highly literal and qualitatively different than representations of experts.

This picture of expertise is probably biased by the highly structured domains in which it has been studied, and the demands of situations in which cognitive expertise is acquired. How do experts solve problems in "ill-structured" domains? How do different experiences lead to different forms of expertise? Hatano (Hatano & Inagaki, 1983) distinguishes between routine (or conventional) expertise and adaptive expertise. Routine experts are outstanding in terms of speed, accuracy, and automaticity of performance, and construct mental models convenient for performing their tasks, but they lack adaptability to new problems. Probably, repeated application of a procedure with little variation leads to routine expertise. Adaptive expertise requires variation and is encouraged by playful situations and in cultures where understanding is valued along with efficient performance. Hatano speculates about how expertise might develop in an efficiency-oriented as compared with an understanding-oriented environment.

I sum up my thoughts about expertise in a set of propositions. These statements represent conclusions from research and occasional broader inferences and speculations.

A Pride of Propositions

1. Expertise is developed over hundreds and thousands of hours of learning and experience, and continues to develop. Studies have been carried on in many domains of work: chessmasters, scientists solving problems, radiologists, skilled technicians, abacus champions, people highly competent in sports, architecture planners, livestock judges, and dairy workers. (See Chi et al., 1982; and Chi, Glaser, & Farr, in press.)

2. In the course of acquiring expertise, plateaus and non-monotoniticles of development are observed which appear to indicate shifts in understanding and stabilizations of automaticity. Karmiloff-Smith (1984), Strauss and Stavy (1982), and Lesgold (1984) have suggested that novices and experts perform better than intermediates on problems that can be solved by surface-level representations.

3. Experts and novices work with similar capacity for processing; the outstanding performance of experts derives from how their knowledge is structured for processing.

4. Expert representations of problems and situations are qualitatively different than novice representations. In the course of developing expertise, problem representation changes from surface representations to inferred problem descriptions, to principled (and proceduralized) categorizations.

5. Expert representations (and schema instantiations) are like fast-access pattern recognitions that reduce processing load and the need for general search heuristics.

6. The representations of experts have actionable meaning; the knowledge of an expert is highly proceduralized and bound to conditions of the applicability of their knowledge.

7. In some domains, experts are "opportunistic planners"; new problem features result in changed problem representation; they show fast access to multiple possible interpretations; novices are less flexible. (E.g., x-ray and medical diagnosis, Lesgold, 1981).

8. Experts can be disarmed by random (or meaningless) patterns and lose their great perceptual ability. (E.g., with a scrambled chessboard experts and novices do equally poorly.)

9. Experts are schema specialized and these schemata drive their performance. (Experts impose a structure on a noisy x-ray; novices are misled by this noise.)

10. Experts are goal driven: given a complex goal, they will represent the problem accordingly; given simple goals, they will think only as deeply as necessary.

11. Experts display specific domain intelligence, not necessarily general intelligence.

12. Novices display good use of general heuristic problem-solving processes (of the Newell and Simon variety, e.g., generate and test, means-end analysis, subgoal decomposition); experts use them primarily in unfamiliar situations.

13. Experts may be slower than novices in initial problem encoding but are overall faster problem solvers. (E.g., analogical reasoning test items, Sternberg, 1977a.)

14. The development of expertise is subject to task demands and the "social structure" of the job situation; the cognitive models experts acquire are constrained by task requirements. (E.g., Scribner, 1984a, 1984b.)

15. Expertise in some knowledge domains may be more generalizable (broadly applicable) than other domains. (E.g., measurement concepts, number concepts, arithmetic problem-solving schema, Carey, in press.)

16. Experts develop automaticity (unconscious processing) particularly of "basic operations" so that working memory is available for necessary conscious processing. (E.g., efficient encoding processes in expert reading comprehenders, Perfetti & Lesgold, 1979.)

17. The experts' understanding may occur after extended practice with procedural skills. (E.g., Karmiloff-Smith, 1984; Strauss & Stavy, 1982.)

18. In solving ill-structured problems, experts employ relatively general methods of problem decomposition, subgoal conversion, and single factor analysis; their thinking is less immediately driven by principles and procedural aspects of their specific knowledge structures.

19. In ill-structured domains, experts work from their memory of an issue's history to represent problems and devise arguments for alternative solutions. (E.g., see analysis by political scientists, Voss, Greene, Post, and Penner, 1983.)

20. Experts develop skilled self-regulatory processes such as solution monitoring, allocation of attention, and sensitivity to informational feedback. (See Brown, 1978; and Gitomer & Glaser, in press.)

21. Expertise can be "routine" or "adaptive and reflective," depending upon the variety of experience and the culture in which it develops. (E.g., Hatano & Inagaki, 1983.)

22. Expert knowledge is not inert; it is highly proceduralized, conditionalized, and compiled. (Anderson, 1983.)

23. Super experts may develop generalizable abilities through the use of mapping and analogy from their own domain to others. (Gentner & Gentner, 1983.)

24. General thinking and problem-solving skills may develop in the course of shifting between many domains, so that the cognitive processes involved become decontextualized. (Glaser, 1984.)

Final Remarks

Increased understanding of the nature of expertise challenges us to inquire how it is learned. It seems evident that expertise is acquired when people continually try to confront new situations in terms of what they know. Increasing ability to solve problems and generate new information is fostered by available knowledge that can be modified and restructured. Thus, when teaching beginners we must build from initial knowledge structures. This might be accomplished by assessing and using relevant prior knowledge, or by providing obvious organizational schemes or temporary models as scaffolds for new information. These temporary "pedagogical theories" are regularly devised by ingenious instructors and could be incorporated more systematically into instruction. Such structures, when they are interrogated, instantiated or falsified by novices in the course of learning and experience lead to organizations of knowledge that are the basis for the more complete schemata of experts. Acquiring expertise is to be seen as the successive development of procedurally oriented knowledge structures that facilitate the processes of expertise.

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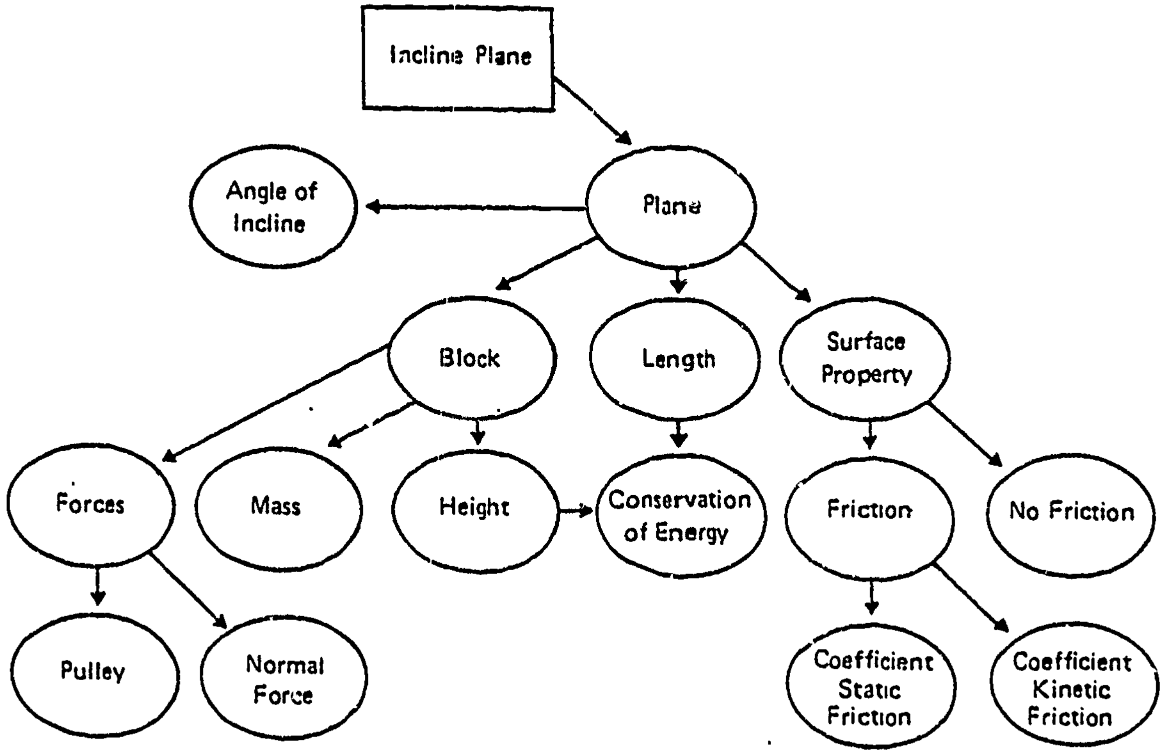

Figure 1. Network representation of Novice H.P.'s schema of an inclined plane.

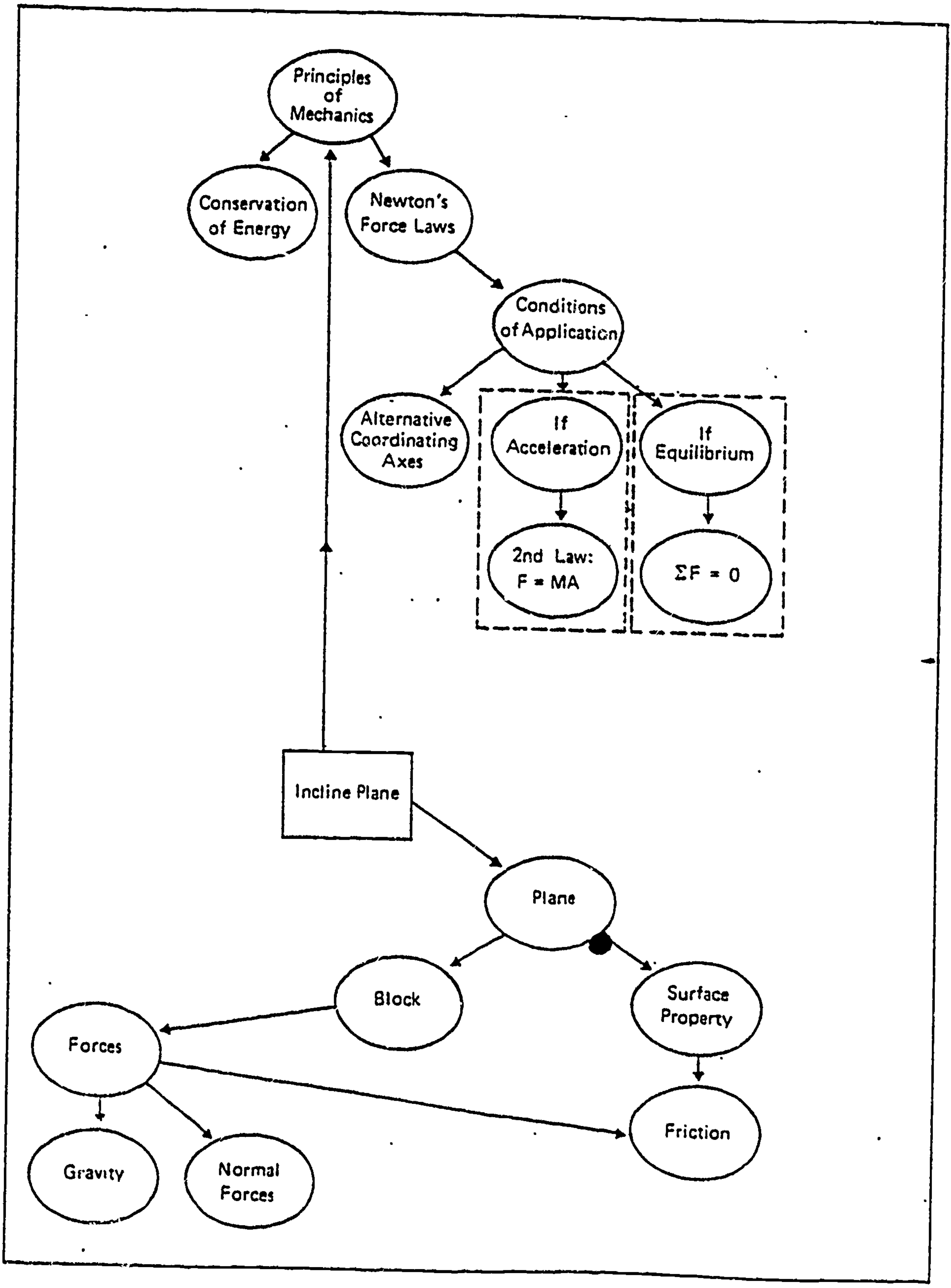

Figure 2. Network representation of Expert M.G.'s schema of an inclined plane.

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