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ABSTRACT

One of the most striking developments in understanding science learning has been the discovery of the extent and persistence of the naive conceptions about the natural world students bring with them to the classroom. In physics and other sciences, students (even those who do well on textbook problems) often do not apply principles they have learned to predicting and describing actual physical events. Investigations have revealed that these students' failures were not due to an absence of theories, but to the persistence of naive theories brought with them to science classes, theories that stand in marked contrast to what they are expected to learn. Evidence is accumulating that these naive theories and the distortions they engender in students' comprehension of instruction are among the principal causes of their failure to achieve understanding in science. Discussed in this paper are: (1) the characteristics of naive conceptions; (2) the influence of naive conceptions on students' interpretations of instructional events; and (3) the implications of this research for designed instruction to facilitate the reconciliation of naive conceptions with scientific theories. (Author/JN)

NAIVE KNOWLEDGE AND SCIENCE LEARNING

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NAIVE KNOWLEDGE AND SCIENCE LEARNING

One of the most striking recent developments in our understanding of science learning has been the discovery of the extent and persistence of the naive conceptions about the natural world that students bring with them to the classroom. It all began with the observation that, in physics and other sciences, even students who do well on textbook problems often do not apply the principles they have learned to predicting and describing actual physical events. Further investigations revealed that these students' failures were not due to an absence of theories, but rather to the persistence of naive theories that they brought with them to the science class, theories that stand in marked contrast to what students are expected to learn. Evidence is accumulating that these naive theories and the distortions they engender in students' comprehension of instruction are among the principal causes of students' failure to achieve understanding in science.

These discoveries are challenging educators and theorists to rethink the role of knowledge in learning. In most of our past thinking about the role of knowledge in learning, emphasis has been on positive transfer--that is, the facilitating effect of knowing something on learning the next concept or skill in a hierarchy (Gagne, 1968; Gagne & Briggs, 1974). With recent research revealing the power of students' existing knowledge of science to <u>interfere</u> with, rather than enhance learning, we are faced with a new kind of instructional problem: how to effectively confront naive conceptions so that the science knowledge represented in the instruction can be successfully learned and applied. This is the fundamental issue which this paper addresses. We consider three main points: (1) the characteristics of naive conceptions; (2) the influence of naive conceptions on students' interpretations of instructional events; and (3) the implications of this research for designing instruction to facilitate the reconciliation of naive conceptions with scientific theories.

Characteristics of Students' Naive Conceptions

The finding that students' naive conceptions are both pervasive and persistent is corroborated by the research of a number of investigators in various countries. Studies conducted by science educators and psychologists (including Brumby, 1982; Clement, 1979; Driver, 1973; Driver & Easley, 1978; Fleshner, 1963; Green, McCloskey, & Caramazza, 1980; Gunstone & White, 1981; Leboutet-Barrell, 1976; Rowell & Dawson, 1977; Selman, Jaquette, Krupa, & Stone, 1982; Viennot, 1980) demonstrate that, for several science content areas:

1. People, young and old, have descriptive and explanatory systems for scientific phenomena that develop before they experience formal study of science.

2. These naive descriptive and explanatory systems differ in significant ways from those students are expected to learn in their study of science.

3. The naive descriptive and explanatory systems show remarkable consistency across diverse populations, irrespective of age, ability or nationality.

4. The naive systems are remarkably resistant to change by exposure to traditional instructional methods.

While the existence of students' naive conceptions has been demonstrated in various science fields, a more coherent discussion of the issues can be presented when attention is focused on one system or macroschema at a time. Hence, the subsequent discussion will focus primarily on the macroschema for the motion of objects. In considering the details of a macroschema for motion, it is convenient to think in terms of knowledge stored in memory as concepts, propositions, and microschemata. (Our definitions for these components of a macroschema are given in Chart 1.) We can then describe the features of each component, the networks of concepts and propositions, and the implications of all the features for the entire macroschema. The relationships of the several components of a macroschema for the motion of objects are shown in Chart 2. In the section that follows, features of each of the macroschema's components in naive theories of motion are described.

Naive conceptions of motion

The resistance of students' naive conceptions to change is particularly striking in the context of mechanics, where prior to formal instruction young people and adults have naive macroschemata for motion that are more Aristotelian than Newtonian (Champagne, Klopfer, Solomon & Cahn, 1980b; Clement, 1979; Driver, 1973; Leboutet-Barrell, 1976; Viennot, 1980). The persistence of remnants of the Aristotelian macroschemata in many "successful" physics students--that is, students receiving high grades in introductory physics courses--has been shown in various studies (e.g., Champagne, Klopfer, & Anderson, 1980a; Gunstone & White, 1981). This research provides empirical support for what physics teachers have long observed: namely, that traditional instruction does not facilitate an appropriate reconciliation of pre-instructional knowledge with the content of instruction (Ausubel, Novak & Hanesian, 1978).

Research carried out by Champagne, Klopfer, and Anderson (1980a) demonstrates that the belief in the proposition, "Heavier objects fall faster than lighter objects," is not readily changed by instruction. In a study of beginning college physics students, about four students in five believed that (all other things being equal) heavier objects fall significantly faster than lighter ones. These results were particularly surprising, since about 70% of the students in the sample had studied high school physics--some for two years. Furthermore, students in the sample who had studied high school physics did not score significantly better than those who had not. Similar findings about the persistence of the heavier-faster belief and other beliefs associated with Aristotelian macroschemata for the motion of objects have been reported in studies of physics students in countries on three continents (e.g., Archenhold, Driver, Orton & Wood-Robinson, 1980; Duit, Jung & Pfundt, 1981; Fleshner, 1963; Gunstone & White, 1981; Jung, 1979; Leboutet-Barrell, 1976; Viennot, 1979).

Naive conceptions are sometimes found in a "pure" state, but more often they are "contaminated" by schooling. Thus, the "pure" naive proposition, "Heavier objects fall faster than lighter ones," is often observed in its "contaminated" form as: "Heavier objects fall faster than lighter ones because gravity pulls harder on heavier objects." The "pure" form is the result of overgeneralization of experience---"After all, stones do fall faster than the leaves."---while the "contaminated" form arises when information learned in science is inappropriately linked to an existing naive conception. It is interesting to note that, in this instance, the existing misconception is reinforced because it is consistent with a proposition which the students view as a "scientific fact."

In studies with both middle-school and college students, certain common elements have been observed in the students' conceptions of motion prior to formal instruction. A general characterization of naive knowledge of motion is as follows:

1. Concepts are poorly differentiated. For example, students use the terms speed, velocity, and acceleration interchangeably. As a result, the typical student does not perceive any difference between two propositions such as these: (a) The speed of an object is proportional to the [net] force on the object; (b) The acceleration of an object is proportional to the [net] force on the object.

2. Meanings physicists attribute to terms are different from the everyday meanings attributed to the terms by the students. For example, students generally define acceleration as speeding up, while physicists define acceleration as any change in velocity.

3. Propositions about motion concepts are imprecisely formulated. The imprecision may be due to students having vague meanings for technical terms or to errors of scale. For example, in the context of an object falling a distance of just one meter, students assert that gravity pulls harder on objects that are closer to the earth.

As the foregoing summary indicates, uninstructed students do have some structured knowledge about many of the concepts related to motion. Their concept structures may be at variance with the structure physicists have for the same concepts, and the meanings attached to terms and propositions relating them may be imprecise or incorrect from the physicists' viewpoint. However, the existence in uninstructed students of structures--even if embryonic--for such concepts as speed, mass, force, and gravity is unmistakable. Furthermore, uninstructed students show evidence of relating these concepts to each other in a macroschema for motion. Although each student may have an idiosyncratic macroschema that in some particulars differs from the macroschemata of other students, there are important common elements among their schemata. To a large degree, then, we can refer to these common elements (described below) as the prototypical students' macroschema, with the understanding that individual variations exist.

The students' macroschema for motion derives from years of experience with moving objects and serves the students satisfactorily in describing the world. Nevertheless, this macroschema is quite different from the formal system of Newtonian mechanics, which is the macroschema for motion that physics courses seek to teach. The content of the naive macroschema for motion can be characterized by the following four rules: (a) a force, when applied to an object, will produce motion; (b) under the influence of a constant force, objects move with constant velocity; (c) the magnitude of the velocity is proportional to the magnitude of the force, so that any increase in velocity is due to increasing forces; and (d) in the absence of forces, objects are either at rest or, if they are moving (because they stored up momentum while previous forces were acting), they are slowing down (and consuming their stored momentum). In the everyday world in which friction is always present, these rules provide a reasonable approximation of the behavior of objects. Moreover, given the insensitivity of the human eye for detecting that an object is accelerating, it is little wonder that acceleration does not hold a central position in the students' macroschema for motion.

To a large degree, the rules of the students' macroschema parallel the descriptive aspects of Aristotelian physics. Although the causal notions of Aristotle (which are often animistic) were not encountered in the students' protocols, it is convenient to refer to their macroschema for motion as Aristotelian. This emphasizes its contrast with the physicists' macroschema, the formal Newtonian system of mechanics, in which the central concept is the acceleration of objects, not their velocity.

Another characteristic of the Aristotelian macroschema is the lack of coordination and consistency of the microschemata of which it is composed. Macroschemata are typically conceived as being composed of a number of microschemata. For example, three possible microschemata for a motion-of-objects macroschema are those for free fall, inclined planes and motion along the horizontal (see Chart 2). In the Newtonian macroschema, these microschemata are coordinated and internally consistent. All are described by the laws of Newtonian mechanics. In contrast, in the naive motion-of-objects macroschema, the situation is quite different. The lack of consistence among the microschemata is striking.

For example, we observe many students who believe that in free fall, two objects of the same size and shape but different mass will fall at approximately the same speed. However, when these same students are asked to compare the approximate times for two objects of different mass to slide down an incline, they predict that the time for the more massive object will be significantly less. One student who had made these conflicting predictions was observed spending 45 minutes comparing the times for two identical toy trucks (one empty, the other loaded) to roll down an incline. At the end of the time he had convinced himself that the times were nearly the same, but he was clearly confused as to why this should be the case. Even when the students are directly confronted with the inconsistencies of their predictions when comparing the speeds of two objects in free fall and on the incline, they see no conflict or problem. When the students observe that the times are approximately equal on the incline, they are confused because they expected that the difference would be much greater. This is but one illustration that the microschemata are uncoordinated, and contradictions that may exist among them are not perceived by the students. The principles that apply to one microschema (free fall) tend to remain localized within the microschema and are not applied to other microschemata (inclined plane, horizontal motion). The expectation that an abstract rule or principle could apply to a range of different microschemata is lacking or poorly developed. Consequently, the microschemata for various physical situations concerning motion can be quite isolated from one another in the students' cognitive structures. A major result of this isolation is that the macroschema is able to accommodate new information locally without producing conflict with other parts of the system. In this way, the system can add principles which may contradict other principles already present and yet not need a major reconceptualization.

Interactions Between Naive Knowledge and Instructional Events

The issue of what role the students' existing knowledge plays in their subsequent learning is of continuing concern in instructional theory and design. Traditionally, it has been assumed that the knowledge that the student already possesses will facilitate further learning (e.g., Gagne, 1968; Gagne & Briggs, 1974). However, our work on mechanics (Champagne et al., 1980a, 1980b; Gunstone, Champagne & Klopfer, 1981; Champagne & Klopfer, 1982a) has demonstrated that students' existing knowledge can also adversely affect their ability to learn from science instruction.

Paralleling the findings of numerous researchers studying other science fields, our research indicates that it is not the students' lack of prior knowledge that makes learning mechanics so difficult, but rather their conflicting knowledge.

The naive macroschema about the motion of objects that students bring to instruction consist of well-formed notions that have been reinforced by the students' experiences. However, their notions may contradict the tenets of classical physics, and it is these notions that tend to interfere with the learning of mechanics. Our research demonstrates specific ways in which students' conceptions influence (a) their observations of experiments and demonstrations; (b) their interpretations of their observations and (c) their comprehension and remembrance of science texts and lectures.

Observations of Experiments

In our work with middle school students, we observed the students' actions and verbal comments as they engaged in discussions or were doing experiments with physical apparatus or simulated experiments on a computer (Champagne & Klopfer, 1982b). Particularly interesting in our observations are the incidents that illustrate the relationship between the students' knowledge and the physical or computer-simulated experiments the students formulated, performed and interpreted. Some representative incidents are recounted in the following paragraphs.

Acceleration. The students observed in one group were operating with multiple meanings of the concept of acceleration. Among these meanings, one popular idea used by several students considered acceleration in a non-quantitative way as a state of increasing speed. In the course of developing this idea more precisely, a student-generated experiment was devised that required the use of both the physical apparatus and the computer simulation of the A-Machine, a short-hand designation for an apparatus consisting of a block resting on a horizontal surface and linked by a string over a pulley to a falling block.

The students wanted to know if the block on the low-friction A-Machine on the air track moves with "uniformly accelerated motion." They used the velocity gates to measure the block's instantaneous velocity at evenly-spaced <u>locations</u> along the air track. From their data, they determined that the block accelerated. However, because they did not have velocity data at equal <u>time</u> intervals, they could not determine if the acceleration was uniform. This dilemma was resolved by doing a computer-simulated experiment in a frictionless physical world. The students correctly determined that in this physical world the block moves with uniformly accelerated motion. They then compared the results and noted that, for data collected either at equal distances (air-track) or at equal time intervals (computer), the acceleration was the same. This is an example of a student-designed experiment that would not be done in the ordinary course of instruction. The convention adopted by physics teachers and in physics textbooks simply assumes that the acceleration of a body is determined by measuring velocity over equal time intervals, so that the question of acceleration over equal distances does not arise. From the student's perspective, however, the question is neither trivial nor irrelevant.

<u>Inertia</u>. Students' conceptualizations of inertia were also the source of several interesting student-generated experiments. Few of the students had a well-developed conceptualization of inertia, but some expressed the belief that it is more difficult to initiate horizontal motion in a heavier block than a lighter block. However, this effect was attributed by the

students to the increases in friction between the block and table. If this assumption is true, the velocity of the block will be independent of the block's mass when the experiment is performed on a frictionless surface. Indeed, one student, when finding the minimum mass of sand required to start a block in motion on the air track, argued that it was not necessary to weight the block since weight (mass) was not a variable that affects motion.

Interpretation of Text

Our evidence for the interactive effects of the students' naive macroschema on their interpretation of texts and lectures is less detailed than that for the effects on the interpretations of experiments. However, results of preliminary analyses of protocol data from studies designed to investigate the existence of the interaction of naive conceptions with science text suggest that the effects are powerful. An observation that we have consistently made when studying middle school students illustrates one aspect of the effect. A common response to the request for an explanation for the students' prediction that an aluminum block will fall faster than a plastic one of the same size and shape is -- "Galileo proved it. He dropped a feather and a coin, and the coin hit the ground first." This response illustrates how a student's belief in the heavier-is-faster rule influences the student's comprehension and remembrance of what is read or heard. We must assume that the student was originally exposed to the complete discussion of the Galileo thought experiment and either did not process or remember the part which conflicted with what she or he believed.

Implications for Instructional Design

Given the consistent research findings of the pervasiveness and persistence of students' naive conceptions and their role in making science learning difficult, what guidance does this research and cognitive theory offer about the nature of instruction that will facilitate the reconciliation of naive conceptions with scientific theories? Further, what instructional strategies that promote this reconciliation can be recommended for use in classroom practice?

Schema Change Theory

Since information processing models of schema development generally have not gone beyond the level of describing stages, the processes by which existing schemata are modified are just beginning to be understood (Greeno, 1980). Nonetheless, several valuable ideas concerning the development of schemata and suggestions for modifying schemata have been offered. The main thrust of these suggestions from cognitive theory is that verbal interactions facilitate schema change.

Two principal mechanisms for schema acquisition and modification have been discussed by Rumelhart and Ortony (1977). Each mechanism is, in a sense, the antithesis of the other. In their view, specialization occurs in a schema when one or more of its variables are "fixed" to form a less abstract schema. Conversely, generalization occurs in a schema when some fixed portion is replaced by a variable to form a more abstract schema. An example of schema specialization pertinent to the motion of objects relates the variable, force ($\underline{F}$), in an abstract schema for Newton's Second Law ($\underline{F=ma}$) to the variable, force, in a less abstract schema for the inclined plane. The highly abstract variable $\underline{F}$ in the Second Law schema, becomes "fixed" in the inclined plane schema to the vector sum of the component of the force of gravity along the incline and the frictional force between the sliding object and the incline. Conversely, generalization occurs when moderately abstract variables, in the inclined plane schema, i.e., the component of the force of gravity along the incline, the frictional force between the sliding object and the incline, and the vector sum of these forces, become generalized to the highly abstract variable F in the Second Law schema.

These hypothesized generalization and specialization mechanisms only describe schema changes and are, in fact, not mechanisms for producing them. While the gradual modification of schemata doubtlessly involves generalization and specialization, in highly integrated schemata more dramatic changes, amounting essentially to a shift to a new paradigm (in Kuhn's (1962) sense), must also take place. To bring about schema change on such a large scale, a dialectical process appears to be necessary. Riegel (1973) points out that the thinking of both adults and children is dialectical, and he proposed that dialectics is "the transformational key" in cognitive development. Anderson (1977) suggests that "...the likelihood of schema change is maximized when a person recognizes a difficulty in his current position and comes to see that the difficulty can be handled within a different schema (p. 427)." As the mechanism for promoting dialectics in the classroom, Anderson advocates the use of a Socratic teaching method. By participating in the dialogues which occur in Socratic teaching, the student is forced to deal with counterexamples to proposals and to face contradictions in his or her ideas. To overcome the attacks of adversaries in the dialogues, the student must construct a new framework of ideas that will stand up to criticism. This reconstruction process produces a modified or new schema, so it may be said that schema change has occurred as a result of the student's participation in the dialogues.

Ideational Confrontation

Ideational confrontation is an instructional strategy that applies the principle of verbal interaction to facilitate schema change. The strategy requires that, in preparation for instructional events (demonstration, laboratory exercise, problem solution, reading text), the physical situation which provides the instruction's context is described for the students. For example, in the case of a demonstration or lab exercise, the instructor displays the equipment and describes the procedure. In the case of a problem, the physical situation is described. In preparation for reading text, the physical exemplars used in the discussion are described.

To illustrate this preparatory phase, the motion of a balloon as the air rushes out of it is frequently used as a teaching exemplar of action and reaction (Newton's Third Law). After the physical situation is described to the class, each student engages in the analysis of the physical situation and states (aloud or written) the concepts, propositions and variables that are relevant to the situation. In the case of the balloon, they would be asked to describe in detail the motion of the balloon as the air is released. After each student has analyzed the situation, a class discussion begins and individual students present their analyses of the situation. An individual student's analysis is elaborated and modified by other students whose analyses are essentially in agreement. Inevitably, controversies arise, usually identified because of differences in predictions about what will happen. Typically, two students with alternative perspectives begin to attempt to convince others of the validity of their ideas. As a student or group of students defends a position, the concepts become better defined, and underlying assumptions and propositions are stated explicitly. The net result is that each student is explicitly aware of his or her analysis of the situation of interest.

At this point, instruction in the traditional sense begins. For example, the instructor does the demonstration with the balloon and presents a theoretical explanation of the results, or the instructor asserts a proposition (e.g., action and reaction) and explains why the example (e.g., balloon) is an instance of the proposition. The students are then asked to compare the elements of their pre-instructional analysis of the situation with the one they have been taught and to identify similarities and differences. This exercise forces the students to confront inconsistencies between their pre-instructional knowledge and the content of the instruction. In the absence of such confrontation, we all too often observe students who possess logically inconsistent school-learned propositions. A favorite example that surfaced in a discussion of objects in free fall concerns two propositions about gravity. The students had learned and were quite satisfied with the proposition that objects of different mass but the same volume and shape fall at about the same rate because gravity pulls equally on all objects. This same group of students also agreed with the proposition that weight is a measure of the pull of gravity on an object. We asked these students to consider this line of reasoning: "Gravity pulls equally on all objects. Weight is a measure of the pull of gravity on an object. Therefore, all objects have the same weight." When confronted with this argument, the students were flabbergasted, but more importantly they were ready to seriously reconsider the validity of the two original propositions.

Ideational confrontation is one important part of the solution to the instructional problem of schema change. Its major contribution is that it creates awareness in the student of his existing macroschema and the need to reconcile it with the scientific concepts and propositions he is trying to learn. In this way, the possibilities for misinterpreting instructional events can be minimized. While the ideational confrontation strategy cannot guarantee that the learning of science will be much less difficult, it does help the student to understand where the difficulty lies. Ideational confrontation and other instructional strategies which guide the student in this way effectively diminish the interference of students' naive knowledge with their learning of science.

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Chart 1

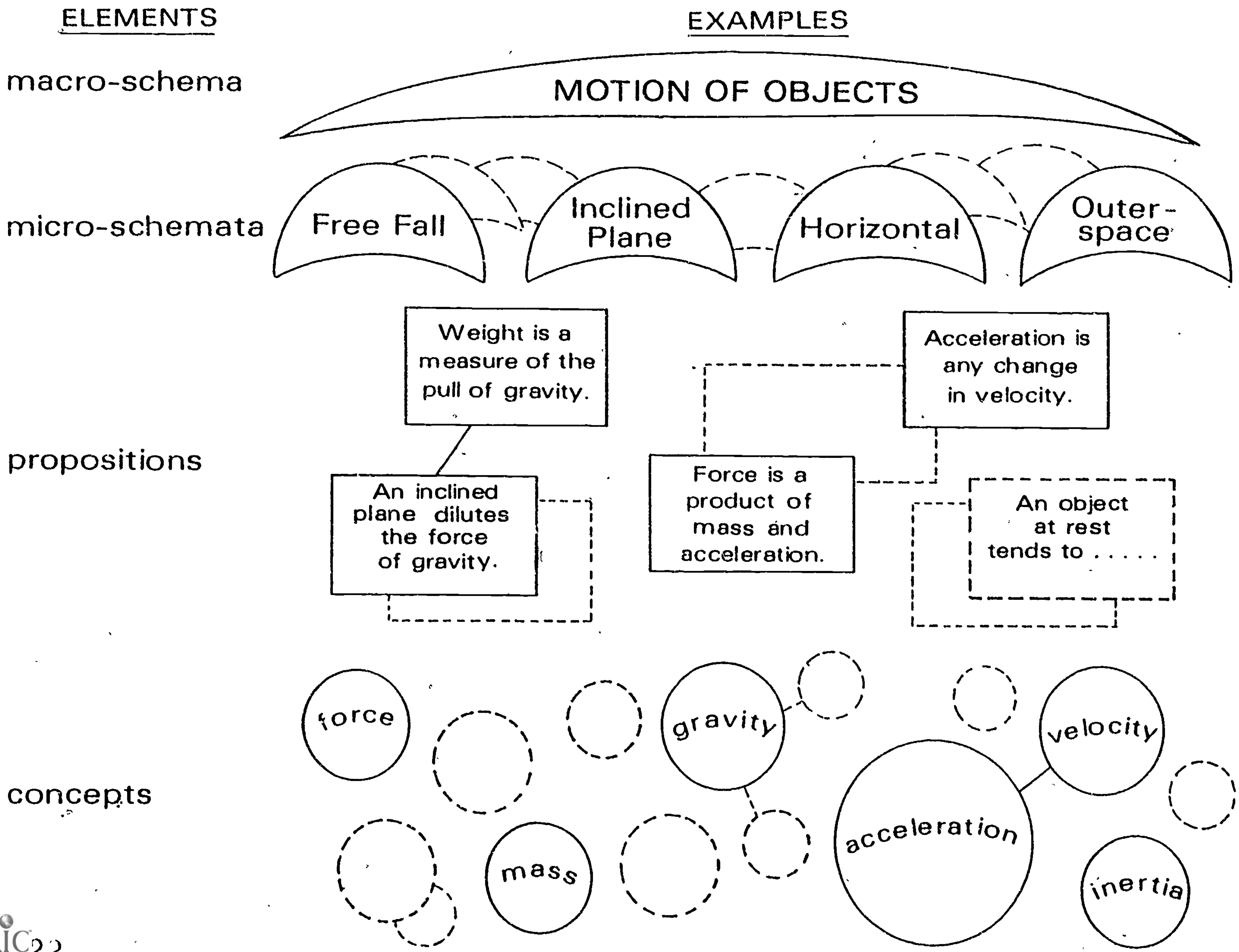
Elements of Knowledge in Memory

concept	An abstract idea derived from or based upon a phenomenon or an assemblage of phenomena in the physical world.
proposition	A rule, principle, or empirical law that asserts a generalization or relationship. A proposition may be an assertion about a certain phenomenon, or it may assert a specific relationship between two or more concepts.
microschema*	A mental structure that guides the analysis and interpretation of an identifiable class of phenomena. A microschema generally incorporates concepts, propositions, and more-or-less integrated networks of these two elements.
macroschema*	A mental structure which encompasses several microschemata. (The notion of a major conceptual scheme used in discussions among science educators about the structure of knowledge corresponds well with the notion of a macroschema.)

*Note: A literary analogue to the cognitive psychologists' notion of schema is genre. Once a reader has identified a story as a mystery, the process of reading is guided by certain expectations (elements) of mysteries. There is the crime, the detective, the victim, the clues (each of which is a concept) and certain propositions that relate the concepts. For example, the detective solves the mystery. Within the genre, mystery, there are sub-genre, all of which have the elements and relations of the mystery but which also have identifiable features which make them identifiable classes. There are Agatha Christie, Mickey Spillane, and Sherlock Holmes mysteries, each of which has its unique features. Each of these classes of mysteries corresponds to a microschema, while the genre of mystery itself it a macroschema.

Chart 2

KNOWLEDGE in MEMORY



ELEMENTS

EXAMPLES

macro-schema

MOTION OF OBJECTS

micro-schemata

Free Fall

Inclined Plane

Horizontal

Outer-space

propositions

Weight is a measure of the pull of gravity.

Acceleration is any change in velocity.

An inclined plane dilutes the force of gravity.

Force is a product of mass and acceleration.

An object at rest tends to . . . . .

concepts

force

gravity

velocity

mass

acceleration

inertia