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ABSTRACT

The methodology and theory of instruction, with special reference to science education, are discussed from the point of view of cognitive deep structure fields. Important difficulties with standard approaches are pointed out, and new avenues for the development of didactical theory are indicated. In Part I of the discussion, a conceptualization of physical deep structure is developed, and three examples are given. In Part II, the role of physical deep structure in psychological development in the teaching of mathematics and science is delineated. It is believed that curricula should be developed upwards, utilizing what children demonstrate as their own way of thinking and own ideas about interesting phonema, rather than downwards from preconceived objectives based on traditional paradigms, including systems of operations. It is suggested that the approach to curriculum planning should be one that respects the natural processes of the child. (DB)

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COGNITIVE DEEP STRUCTURE AND SCIENCE TEACHING*

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Resumé

The role of concrete operational systems in mental development and their explanatory power for much of what one sees children do during the day seems to us somewhat limited. The question why at a given time in the child's life he subjects certain aspects of a physical system to concrete operations and not others, and why certain aspects are subjected to concrete operations earlier than others, Piaget only explains in very general terms, and in fact not in terms intrinsic to concrete operations at all.

Continuous deep structure fields and subfields are postulated on the basis of clinical interviews and classroom observation, which can account for décalage and other phenomena outside the capacity of operational systems to explain.

The methodology and theory of instruction, with special reference to science education, are discussed from the point of view of cognitive deep structure fields pointing out important difficulties with standard approaches and indicating new avenues for the development of didactical theory.

Introduction

Traditionally the relevance of Piagetian theory to education for children ages two through 12 has been considered based on preoperational and concrete operational systems (Harvey, 1969; Lovell, 1971). However, the role of concrete operational systems in mental development, and their explanatory power for much of what one sees children do during the day seems to us somewhat limited. The question why at a given time in the child's life he subjects certain aspects of a physical system to concrete operations and not others, and why certain aspects are subjected to concrete operations much earlier than others, Piaget only explains in very general terms, and in fact not in terms intrinsic to concrete operations at all (Inhelder and Piaget, 1955). More generally, one can raise the question why, at a given time in the child's life, always certain aspects of a physical system are isolated and referred to by the child, and not others, why the child sometimes prefers to think in terms of states of a variable, sometimes in terms of changes, and why there is always lack of differentiation or confusion between certain aspects, but not between others. Finally, the very raison d'être of concrete operations, their role in explaining conservation, can be questioned. As far as we can see, the particular system of operations involved in dealing with a physical system (e.g., balancing the arms of a horizontal beam) typically consists of only a small number of items (say 20), and it is hard to see how such a small structure, as a structure, can explain conservation if one doesn't attribute more meaning to the operations as individual entities.

By cognitive structures one means theoretical entities with which can be associated, or to which can be referred, specific patterns of behavior, or aspects of specific patterns of behavior, on different occasions over a period of weeks or months or years. Piaget's schemes are cognitive structures in this sense. They can be largely conceived of, and in fact can be formalized and explicated, as finite

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relational structures in which some of the element and relation terms refer to (external or internal) actions. This is true of sensory-motor schemes (Witz, 1971c), of preoperational structures (Witz, 1971a), and particularly of systems of concrete operations which are explicitly thought of as operations on given data (Inhelder and Piaget, 1955, p. 249).

Now the fact that there are discernible patterns in the application of concrete operations, that there are natural conjunctions and nondifferentiations between certain variables and not others, etc., suggests that we envisage a new realm, a new level of cognitive structure that accounts for these facts. We will call this level physical deep structure. In the preoperational and the concrete operational child, physical deep structure is precisely a structuring in what Piaget, in the passage cited, calls given data, i.e., it is a continuous structuring of processes of perception of motor activity and cannot be represented by discrete relational structures. In what follows we first attempt to develop a conceptualization of physical deep structure, and then discuss some of the perspectives in mathematics and science teaching which it opens up.

Part I. Physical Deep Structure

Section 1

At each moment of time, physical deep structure is a nexus of identifiable overlapping parts called deep structure fields (*d.s.f.*'s). When the child is interacting with a particular physical system, or when he contemplates one, a d.s.f. comes into play, gives rise to what appears in introspection as intuitive feelings of weight, momentum, inertia, etc., and strongly influences his externally observable behavior. Each d.s.f. will be conceived as a continuous dynamic form, or flux; it keeps its identity as a cognitive structure over a period of months, or years, but may be completely transformed in the course of development. We discuss three examples.

Example 1.[1/] Cathy, aged 12, is given several different lengths of string, a half dozen balls of different diameters and materials which can be suspended at the ends of the strings, and a support stand, for making pendula. As in Inhelder and Piaget (1955), she is asked to find out what makes the period change. After demonstrating the effect of length with a golf ball, she says:

C: "To make it come back faster you make the string shorter, and to make it come back slower you make the string longer." (Cathy stands looking at the experimenter as though she has finished the task.)

E: "Is that the only thing that will--?"

C: "Well, if you swing it faster like that (pushes the golf ball), it will come back faster, but if you just let go like that it will come back later." (She lets go from a small amplitude and watches it swing.)

Cathy tests a rubber ball. Next she tries out a metal ball on a long string, then hangs the golf ball on a short string, and sets both balls swinging.

1/ All observations quoted here and in the later sections of this paper were collected by Rosalind Driver and are reported in her thesis (1971). We are extremely grateful to Mrs. Driver for this material.

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C: "If it's lighter it comes back faster--and this one's heavier so it comes back slower."

The most important features here are that the behavior is labile and generally subordinated to the task of controlling the swing; Cathy is obviously familiar with quite subtle aspects of the pendulum's operation and in fact she twice makes doubly sure she gets the desired result. (She contrasts <u>pushing</u> from a <u>large</u> amplitude with <u>letting go</u> from a <u>small</u> amplitude, and she contrasts a <u>heavy</u> ball on a <u>long</u> string with a <u>light</u> ball on a <u>short</u> string.) Now <u>these features</u>, together with the fact that a pendulum is a rather unique physical system (in the sense that sufficiently different variants, like a long heavy bar freely suspended at one end, are unlikely to be part of the child's experience), lead us to envisage a single d.s. field, P, that comes into play on this and similar pendulum occasions and that has as identifiable sub-d.s.f.'s (a) pushing, (b) just letting go, and (c) a concept of weight.

The d.s.f. P is typical of d.s. fields that underly the activity of younger children (ages four to six) in situations involving specific types of physical apparatus, such as turning wheels on an axle, pushing or rolling larger objects, etc. These d.s. fields are specific to the type of systems involved, encompass many aspects of operations of the system as a whole, and contain relatively few subfluxes that are shared across many situations (like a feeling for weight).

<u>Example 2</u>. <u>Ricky's concept of inertia</u>. Ricky, aged 12, is working with several pieces of apparatus (horizontal track with plunger, P.S.S.C. carts with bricks, a toy truck and pendulum materials).

(On the horizontal track:)

(1) R: "Actually, the heavy balls might go farther because of their inertia. If they get started they are harder to stop--."

(2) R: (After he shoots several balls.) "This must be a middle weight (pointing to the ball that went the farthest). It won't have too much friction and won't get too little inertia." (In other words the heavy balls will not go so far because of greater friction, and the light balls won't go so far because they have little inertia; hence, there must be an optimum middle weight.)

(On the carts:)

(3) R: (After pushing a cart and watching it coast.) "Well, it's <u>pretty</u> <u>/much/</u> pressed forward, and it got it moving (pushes cart) then the wheels begin to pick up on their own and they may--it took up a little bit. The force you have given it makes the wheels go, and once they have got rolling some of their inertia...make(s) them go faster...."

(4) E: (Pushes cart slowly across table.) "Ricky, what are the forces on this cart?"

R: (He names several.) "...and inertia would work two ways, it's trying to stay still now and once it is set going it's trying to keep going."

(5) E: "Inertia is a force, is it?"

R: "Not really."

E: "How would you describe it?"

R: (Pause.) "A tendency--it's just something that would operate on a body that has no unequal force on it."

(6) E: (After Ricky had predicted graphically the results of "exploding" a system of two carts, one loaded with two bricks.) "What would happen if you did this experiment in empty space?"

R: "I guess this one (with bricks) would still go slower. It needs more force to overcome its inertia."

(Concerning a picture of a truck pulled in opposite directions by two rubber bands (Figure 1):)

(7) R: (What would happen if one rubber band were cut?) "...the truck will tend to stay still and then it will start to go faster...."

E: "What makes it do that?"

R: (Quickly.) "Inertia."

(8) E: "What do you mean by inertia, Ricky?"

R: "Well, ...the body will stay right here unless you have unequal forces acting on them."

(9) R: "...inertia isn't strong enough to overcome the rubber band, so the rubber band pulls it. Actually this will all take place fairly fast."

(10) R: "...the inertia doesn't have much force in relation to a normal rubber band."

(11) E: "How could you increase the inertia of the truck?"

R: (Seven-second pause.) "Make it heavier. So we could put a weight on there. But actually that might begin to tend on the friction."

(12) R: "...The inertia would not be enough to stop it at any force, because inertia is just the tendency to stay still when you have a force acting on it. So if you have a rubber band pulling however much inertia you have it would start coming. If there wasn't any friction, say in outer space, and you just had this rubber band here and let go it would go slowly but it would move."

(On the pendulum:)

(13) E: "Is there anything else that might make a difference?"

R: "I'm not too sure, but I think there is another equal weight balance like there was over there. There will be a middle weight where things will swing faster because when it gets too heavy the thing won't go very far after it will be caught. If it's too light it won't gather enough speed coming down to go up very far."

An ongoing conception of force applied to an object being met by the inertia of that object seems implicated in seven out of 13 comments ((1), to some extent (3), (4), (6), (7), (9), (12)), and in quite different physical situations. This leads us to envisage a d.s. field S_1 that underlies this conception and comes into play in the seven occasions mentioned. It is highly significant (and we will come back to this below) that S1 is related by Ricky explicitly to both starting and stopping objects, and that inertia is treated sometimes as an intrinsic property of objects (like weight), sometimes as something they acquire (in (2)). Further according to (5) and (8), Ricky thinks of inertia primarily in a context where the object is subject to a balanced system of forces. From other interviews his conception of a balanced system of forces is a mobile one that is underlain by a d.s. field S_2, so that (7) and (8) indicate a common d.s. field S_o which contains both S_1 and S_2 as subfields. Finally the fact that the comments from (8) to (12) are made within a span of two minutes about the same system allows us to speak of a still larger inertia nexus S, which contains S_o, S_1, S_2 as subfields.

Compared to Cathy, Ricky's understanding of the pendulum can be described not so much in terms of a single d.s. field concerned with aspects that arise naturally in manipulating the system, but rather as a multiplicity of highly identifiable and strongly interacting d.s. fluxes like S_1 and S_2. Although these structures have their origins in identifiable subfields of a d.s.f. for pendulum-type systems like Cathy's d.s.f. P, their strength and the multiplicity of their interactions has for all practical purposes obliterated the original d.s.f. (Ricky applies with ease 15 or so concepts to the pendulum.) Generally speaking, system specific d.s.f.'s like Cathy's P seem to underly some of the structures in four-year-olds which we have described as frameworks and activity structures (Witz, 1970, 1971b; Knifong, 1971). Indeed the method we have been using for identifying d.s.f's is reminiscent of the method for identifying frameworks described in Witz (1970).

Example 3. Cathy's concept of inertia.

E: "What will happen when I push this cart (a block of wood on wheels)?"

C: "It would go that way and stop, unless you push it again."

E: (Pushes the cart.) "How would you explain what you see?"

C: "Well, the force of your hand is stronger than the resistance this (the cart) has, so it moves."

E: "What is the resistance this has?"

C: "The block of wood."

Although we have only this single instance, we consider ourselves justified in postulating as a single d.s.f. a conception of inertia (she says, "resistance") against attempts to move an object. In contrast to Ricky, this is not extended to stopping a moving object, and although attributed to the object (rather than to the experience of pushing as an undifferentiated whole) it is not considered a property of the object.

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Section 2

When a lump of clay is put in a glass of water, six- to seven-year-old children will say that the water will rise because the ball is heavy. Why do they say this? Why do they bring in the notion of weight? Why do they think about the rising of the water rather than, say, the final water level? In the theoretical framework of the preceding section, we would say that the child has an underlying conception, a clearly identifiable d.s.f., t_1, that weight pushes water, or causes water to move, and that this d.s.f. is usually involved in common everyday situations such as immersing a big heavy object in water in the bathtub or in a sink and at the same time feeling and watching the water rise, or pushing a rubber ball under water, etc., etc.

We can expand this example to explain some of the behavior of nonconservers in the conservation of volume task. When the ball of clay is made into a pancake, the child may say that "when you spread it out it gets lighter." This by itself would indicate an identifiable d.s.f., t_2. In addition, t_2 seems to interact with t_1 to form a new d.s.f., t_o, which underlies the apparent inference.

We could go in this way and try to understand why turning the submerged pancake from the horizontal to a vertical position raises the water level (rather than lowers it) and even perhaps why there is more water in the tall cylinder than in the wide one (rather than less)--all aspects of the child's thought which are of vital importance to education but which are not explained by operations. More generally we believe that many of the "incoherent" causal systems of pre-operational children in the standard tasks--conservation, classification, seriation, etc.--can be understood in terms of deep structure and utilized constructively in cognitive growth.

Abstracting from the examples we have discussed so far, we can say that two typical phenomena associated with d.s.f.'s are: (1) natural confusions and mixtures of aspects (like the mixture of weight and water rising above) and (2) natural conjunctions when varying already well-identified aspects of the system (like the conjunctions of pushing and amplitude and of length and weight in Cathy). We believe that it is possible to study d.s.f.'s by looking at patterns of mixtures, and at patterns of conjunctions within the same child across many different physical situations.

Section 3

By giving a physical analogy ("this is like when...") or by employing concept terms like "heavy," "force," "resistance," "inertia" ("that's because it is heavier," "inertia keeps it going"), the child in effect asserts that the physical situation a_1 in front of him is in a certain respect equivalent, or similar to, other physical situations a_2, a_2', a_2''....The fact that such an equivalence or similarity is asserted with confidence, and is introduced spontaneously by the child, or in response to very general questions ("why?", "how does this work?", etc.)--in short, that a physical phenomenon has been identified by him as a unique whole that underlies many different situations--that fact poses theoretical problems of the first magnitude. We will argue that conventional conceptualization on this point is wrongheaded, and that one needs new theoretical entities like d.s.f.'s to account for the difficulties.

The conventional finite structural account of how physical equivalences, for example, come about is in terms of partial correspondences (isomorphisms). Schematically, if a child declares a situation a_1 to be just like some other situation a_2, one tries to distinguish in a_1 features, elements or relationships, which form a structured system A_1 isomorphic to a corresponding system A_2 of features, elements or relationships in a_2. One then assumes that there is a finite system of schemes which assimilate substructures of A_1 and A_2 in the same way, i.e., preserving the correspondence. The equivalence, then, is made because there are enough points of correspondence between the two situations which are assimilated by existing schemes of the child.

Let us examine this conceptualization in a concrete case: The judgments made by Tom (age 12) about scale readings for the same object under different circumstances. Tom predicts that a cart will give a greater scale reading on a spring balance near the top of an inclined plane than near the bottom (Figure 2), and he expects that when an object is freely suspended, the spring balance reading would be higher if the object is raised higher up. While holding two marbles in his hands, one higher than the other, he explains:

T: "The higher it gets the more effect gravity is going to have on it because--um--because, like if you just stood over here and someone dropped a pebble on him it wouldn't hurt him. But like if I dropped it from an airplane it would be accelerating faster and faster and when it hit someone on the head it would kill him."

When asked what the spring balance would read if a thousand-gram weight resting on the table were lifted by means of the scale one foot above the table:

T: "...you won't get it to register until it (the weight) is up in the air and then, when it is up in the air, the gravity would have more effect on it. So I'd say about 1,400 grams."

E: "Why?"

T: "Because it weighs 1,000 but gravity--. That's just 1,000 sitting on the table, and the table stops gravity from pulling down, but in the air there is nothing to stop it, so gravity can pull it down further."

Finally in the discussion on free fall, E asks:

E: "If we hung an object into the spring balance and we climbed up a step ladder to the ceiling and took a reading of the spring balance and then climbed down and repeated our readings on the floor, what can you tell me about those readings?"

T: "I think it would be equal--because gravity is pulling it down as hard as it can but it's being held up so it can't accelerate, it just has to hang there because of the spring."

We see that Tom has combined a conception of the effect of gravity with that of the possibility of movement of the object on which gravity acts. Now all three situations can be seen to involve essentially the same finite structural setup (A_1, A_2 above). See Figure 3.

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Instead of taking the conventional position that the child makes his judgments because there are demonstrable isomorphisms between the situations (Piaget, 1971), we believe that the fundamental problem is to explain how the child invariably picks out a structured system of aspects (features, elements, relationships) which on later examination turns out to be the one most consistent with his other choices, and why his analysis of the situation doesn't fluctuate from moment to moment. In other words, we would argue that, in view of the many possibilities of analysis of a given situation by existing schemes of the child, one has to assume a deeper, more global active organizing unit like a d.s.f. to explain the stability of his conceptions--the sureness of his judgments, their lack of fluctuation vis-a-vis a given situation, and their consistency across diversely related situations. Consequently, partial isomorphisms between situations are extremely valuable analytical instruments in that they document the equivalences which the child makes, but they do not explain them.

Similar problems arise when one tries to model in real time, purely on a basis of objectively specifiable partial isomorphisms between situations, how it comes about that the child, when asked to explain one particular situation a_1, gives as analogy a physical situation a_2 rather than another one, a_2'. As a rule, the child is familiar with dozens of situations isomorphic to a_1 in the aspect he has in mind; why is it that he produces a_2?

Section 4

The physical judgments discussed in Section 3 were, of course, based on verbal reports. When one asks for the earliest nonverbal behavior patterns which seem to imply or presuppose comparable "judgments" one is led to the tertiary circular reactions described in La Naissance de l'intelligence--the behavior pattern of the support, the behavior pattern of the string, etc. When the behavior pattern of the support appears, for example, it is suddenly generalized over an enormous range of object-on-support situations, and there is initiation of action and sureness of action by the child in diverse situations--precisely the characteristics we get when we extrapolate equivalencing based on d.s.f.'s backwards to less verbal age levels. Accordingly we identify the earliest d.s.f.'s with the tertiary circular reactions, and regard the relationships "x is supported by y," "the string is connected to x," and "the stick in my hand pushes x" as the earliest d.s.f.-based concepts.

Section 5

At this point we must consider a deeper issue which we glossed over in the considerations in Section 3, namely, the mobility of deep-structure concepts, ranging from mere analogy (identification of a type of experience, like Tom's airplane story) to a full-fledged physical property of objects (like Ricky's concept of inertia). There is no doubt that treating weight, resistance, inertia as properties of objects, or treating force, resistance, inertia, as properties of physical events, etc., constitutes an active achievement of the child that must be explainable in terms of specific internal dynamical mechanisms which deeply affect the correspondences the child makes.

We can arrange the above examples in a series according to apparent increasing mobility of the concept involved:

1. Tom's airplane story: mere analogy, or identification by the child of a type of experience.

2. Cathy's response that the resistance is "the block of wood": identification has progressed to localization of the phenomenon in a part of the situation in front of the child.

3. "You get different results y because of x" (e.g., because it's heavier, because of the force, etc.): Here x is not yet a property of the object, or of an interaction between objects, but the child has a way of referring to it. Certainly much more is going on than that the child merely connects x with y.

4. Ricky's notion of inertia as a property of objects.

In Section 3 we lumped these behavior patterns together as all being expressions of physical equivalencing, of identification by the child "in his muscles" of a common physical phenomenon. We now propose further that formation of physical property concepts is intrinsically connected to the nature of d.s.f.'s, although syntactical elements may, of course, be involved. One line of evidence for this view is the fact, beautifully brought out by Piaget, that in tertiary circular reactions, which we have characterized as proto d.s.f.'s, the child's behavior is for the first time directed by properties of objects (by "independent centers of forces," as Piaget says (1936, p. 277)). A detailed model for this shift from a world of completely action-bound happenings to a world "stocked with independent centers of forces," say a model in the form of a well-defined dynamic internal mechanism does not yet exist; we are working on this problem in the context of a detailed real-time parallel process simulation of systems of sensory-motor schemes in infants (Witz, 1971d). Insofar as d.s.f.'s seem to be essentially continuous entities, our previous considerations suggest that this shift is a global effect of continuous kinesthetic systems which cannot be usefully modelled in terms of reorganization of small discrete systems of schemes.

Perhaps closely connected with the preceding is a second property of d.s.f.'s which we also find in tertiary circular reactions: their generative power, that is, their capacity to drive and sustain the child's interaction with a given physical system. On the one hand, Piaget's analysis (Piaget, 1936) tends to show that the type of exploratory activity that appears at the stage of tertiary circular reactions has qualitatively completely new characteristics which cannot be explained on the basis of earlier types of dynamics between schemes. (This is also a problem we are studying rigorously in the simulation project mentioned above.) On the other hand, at the level of four-year-olds, the question of generative power of d.s.f.'s raises the question of the detailed dynamical integration of "deep structure" fields and "surface" activity structures into unified functional systems.

Part II. Cognitive Deep Structure and Math and Science Education

A half dozen of the most difficult problems in curriculum design and pedagogical practice, brought to light by the efforts of the past decade (particularly in science and mathematics education) can be approached from a much more promising point of view if one pays serious attention to cognitive deep structure.

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In mathematics education, controversy has centered on three major problems which, as far as instructional practice is concerned, still remain largely unsolved (Easley, 1967): the justification of logic as a tool for understanding mathematics, the problem of incorporating heuristics into instruction, and the problem of teaching mathematics so as to make applications in other fields far easier than now seems to be the case. One approach to this last problem was considered by the Cambridge Conference on School Mathematics in its report (1968) on the correlation of mathematics and science education, but practical programs for bringing about a genuine resolution are still needed. In science education, the problem of identifying the processes of scientific thought is an old one whose current interest is illustrated, for example, in the debate between Atkin (1966, 1968) and Gagné (1966, 1968), and Easley's review (1971a), and the question concerning the role of the teacher (Hanson, 1970; Ashenfelter, 1970) has been answered quite differently by Hawkins (1969) and by Karplus (1964).

By taking the nature and role of physical deep structure in psychological development into account, we believe that some progress can be made on all of these problems. In all of the above problems, physical deep structure, operational systems, algorithmic systems (formal calculi) enter and interact in different ways. The problem is to find out how they can best be utilized to help each other, and how each can challenge the other to get more educational growth.

Section 1

The traditional position is that operations are the most important intellectual achievement for the age levels in question (Piaget, 1967; Lovell, 1971), and educators have concerned themselves with operations in various ways (e.g., they have attempted to match the school experience to them (Hunt, 1971), to extend their applicability horizontally to other situations (Peel, 1964), thus removing the effects of décalages horizonteaux, and to accelerate their rate of development (Sigel and Hooper, 1968). Our position is that, instead of being primarily concerned with operations as an end, we think educators should be concerned with development and utilization of deep structure.

First, we would say that deep structure causes difficulties in school programs, even those which are designed around operations, because (a) it prevents the development of new paradigms (à la Karplus), or it may inhibit the acceptance of conclusions to which operations would otherwise lead, (b) it may prevent the application of operations which are already developed, and (c) through the effects of (a) and (b), it leads to frustration with some, if not most, of the academic work of schools and to self-abnegation, especially in mathematics and science.

To illustrate these points, in the science class which Mrs. Driver studied there were heated arguments on whether an object on a table is "held up" by the table or whether the table is "pushing up." Children that insisted on "held up" had considerable difficulties in assimilating the "balanced system of forces" paradigm even after several weeks of instruction. Or again, in Anderson's study (1965), children aged six to seven mastered the all-but-one strategy in artificial tasks, in which independent and dependent variables were clearly identified, but they were typically unable to apply it to a natural physical system. We would say that this was due to various types of conflicts between the system-specific deep structure (and its subflumes) and the operational system: "natural mixtures" obscure the clarity of perception of variables needed in the strategy, "natural

conjunctions" may override operation of the strategy, the dependent and independent variables in the strategy may not coincide with the aspects the child naturally manipulates and the results he seeks respectively in the system-specific deep structure, etc.

Section 2

We believe that a great deal more valuable growth is possible than is usually envisaged by educators--growth that is neither dependent on mastery of operations which children may lack nor on the acquisition of scientific paradigms, or algorithmic systems as ends or as tools. For example, ten-year-olds often are capable of extremely subtle and interesting explanations of the dynamics of a pendulum's swing (Easley, 1971b): They see momentum, two or more kinds of weight, continuously changing velocity, angle, swing, force, and power, or energy, impulse, inertia, as well as the period and length, which are classically all that is studied.

Once it is realized that children have and can develop rich systems of deep structure to explain physical phenomena, one can develop experiments, not in the sense of systematic control of variables, but in a more naturalistic and open sense of finding various ways of experiencing and representing aspects of the physical system which would lead to the formation of new deep structure as well as deep-structure fused operational and algorithmic systems.

Put differently, we feel that curricula should be developed upwards utilizing what children demonstrate as their own way of thinking and own ideas about interesting phenomena, rather than downwards from preconceived objectives based on traditional paradigms, including systems of operations. Consider, for example, the 12-year-olds in the science class who objected to the table "pushing up." Now, some of these children had a conception to the effect that the "holding up" of the table was a fixed characteristic of the table which did not vary with the weight placed on it. There appears to be no point either in instructing these children in Newton's postulate and its application to statics nor in postponing further study of mechanics until they might have discovered action and reaction on their own. Rather, one can adapt the instruction to fit their intuitions, encouraging a development of self-conscious analytic techniques. For example, one can start experimenting with certain types of flat materials which respond with a noticeable "give" to the application of heavy objects. In this way the d.s.f. underlying "holding up" is modified and embedded into a larger d.s.f. underlying "give" and, at the same time, the latter is fused with a reversible operational structure ("give" vs. "holding up"). As a convenient measure of the "give" of each piece one can then introduce the ratio of distortion to the weight applied, and in this way tie the d.s.f. to an algorithmic system (numerical ratios).

Now the d.s.f.'s underlying "holding up" and "giving," as explained above, are natural cognitive objects for carrying the concept of electrical resistance (and in a similar way, Tom's d.s.f. underlying gravity plus possibility of motion is a natural cognitive structure for carrying the concept of electrostatic potential). Accordingly the procedure above uses intuitive systems appropriate to electricity to understand mechanics. But this brings us back again to the fundamental issue concerning the whole approach we as educators should take to science. The reigning attitude in curriculum planning is to develop a subject-matter area like mechanics logically from the ground up as a separate compartment--that is, to plan the curriculum downward, from preconceived and traditional objectives. We believe a different approach is needed--an approach that respects, not compartmentalization and preconceived logical or philosophical analysis, but the natural processes of the mind.

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Figure 3

Situation 1

table
is holding
x up

x has
no possibility
of movement

table
stops
gravity

gravity
is pulling as
hard as it can

gravity has
constant effect
1000 grams

Situations 3
(object x held from ladder)

(when spring has
reached maximum extent)
spring is
holding x up

x has
no possibility
of movement

spring
stops
gravity

gravity is
pulling as
hard as it can

gravity has
constant effect
independent of
height

Situations 2
(object x in air at different heights)

there is nothing
holding x up

x has
possibility
of movement

there is
nothing to
stop gravity

gravity is
pulling as hard
as it can

gravity
has more
effect