Accommodation of a Scientific Conception: Toward a Theory of Conceptual Change*

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It has become a commonplace belief that learning is the result of the interaction between what the student is taught and his current ideas or concepts.[1] This is by no means a new view of learning. Its roots can be traced back to early Gestalt psychologists. However, Piaget's (1929, 1930) early studies of children's explanations of natural phenomena and his more recent studies of causality (Piaget, 1974) have perhaps had the greatest impact on the study of the interpretive frameworks students bring to learning situations.

This research has led to the widespread study of students' scientific misconceptions.[2] From these studies and, particularly, from recent work by researchers such as Viennot (1979) and Driver (1973), we have developed a more detailed understanding of some of these misconceptions and, more importantly, why they are so "highly robust" and typically outlive teaching which contradicts them (Viennot, 1979, p. 205).

But identifying misconceptions or, more broadly speaking, "alternative frameworks" (Driver & Easley, 1978), and understanding some reasons for their persistence, falls short of developing a reasonable view of *how* a student's current ideas interact with new, incompatible ideas. Although Piaget (1974) developed one such theory, there appears to be a need for work which focuses "more on the actual content of the pupil's ideas and less on the supposed underlying logical structures" (Driver & Easley, 1978, p. 76). Several research studies have been performed (Nussbaum, 1979; Nussbaum & Novak, 1976; Driver, 1973; Erickson, 1979) which have investigated "the *substance* of the actual beliefs and concepts held by children" (Erickson, 1979, p. 221). However, there has been no well-articulated theory explaining or describing the substantive dimensions of the process by which people's central, organizing concepts change from one set of concepts to another set, incompatible with the first. We believe that a major source of hypotheses concerning this issue is contemporary philosophy of science, since a central question of recent philosophy of science is how concepts change under the impact of new ideas or new information. In this article we first sketch a general model of conceptual change which is largely derived from current philosophy of science, but which we believe can illuminate

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[1] See, for example, Ausubel (1968).

[2] See Driver and Easley (1978) for an excellent review of research in this area.

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learning as well. We then illustrate some features of this model from interviews with students studying special relativity in physics. Finally, we derive some pedagogical implications.

Our central commitment in this study is that learning is a rational activity. That is, learning is fundamentally coming to comprehend and accept ideas because they are seen as intelligible and rational. Learning is thus a kind of inquiry. The student must make judgments on the basis of available evidence. It does not, of course, follow that motivational or affective variables are unimportant to the learning process. The claim that learning is a rational activity is meant to focus attention on what learning is, not what learning depends on. Learning is concerned with ideas, their structure and the evidence for them. It is not simply the acquisition of a set of correct responses, a verbal repertoire or a set of behaviors. We believe it follows that learning, like inquiry, is best viewed as a process of conceptual change. The basic question concerns how students' conceptions change under the impact of new ideas and new evidence.

The Epistemological Base

Contemporary views in philosophy of science suggest that there are two distinguishable phases of conceptual change in science. Usually scientific work is done against the background of central commitments which organize research. These central commitments define problems, indicate strategies for dealing with them, and specify criteria for what counts as solutions. Thomas Kuhn (1970) calls these central commitments[3] "paradigms," and paradigm-dominated research "normal science." Irme Lakatos (1970) labels scientists' central commitments as their "theoretical hard core" and suggests that these commitments generate "research programs" designed to apply them to and defend them from experience.

The second phase of conceptual change occurs when these central commitments require modification. Here the scientist is faced with a challenge to his basic assumptions. If inquiry is to proceed, the scientist must acquire new concepts and a new way of seeing the world. Kuhn terms this kind of conceptual change a "scientific revolution." For Lakatos it is a change of research programs.

We believe there are analogous patterns of conceptual change in learning. Sometimes students use existing concepts to deal with new phenomena. This variant of the first phase of conceptual change we call *assimilation*. Often, however, the students' current concepts are inadequate to allow him to grasp some new phenomenon successfully. Then the student must replace or reorganize his central concepts. This more radical form of conceptual change we call *accommodation*.[4]

This view of inquiry and learning involves one additional feature. We believe that inquiry and learning occur against the background of the learner's current concepts. Whenever the learner encounters a new phenomenon, he must rely on his current concepts to organize his investigation. Without such concepts it is impossible for the learner to ask a question about the phenomenon, to know what would count as an answer to the

[3] In this article the terms "commitments," "concepts," and "conceptions" are equivalent. Although these terms (particularly the latter two) refer to differing levels of conceptualization, we do not distinguish among the levels in this article.

[4] These are Piaget's words, but in using them we do not intend any commitment to his theories.

question, or to distinguish relevant from irrelevant features of the phenomenon. Without concepts the world is and remains William James' "blooming buzzing confusion." Borrowing a phrase from Stephen Toulmin (1972), we refer to those concepts which govern a conceptual change as a "conceptual ecology."[5]

Our work has focused on the kinds of radical conceptual changes which we describe as accommodations. How do accommodations take place? Recent work in philosophy of science suggests that this question be divided into two. The first concerns the conditions under which an accommodation is likely to take place. When will individuals find it reasonable to undertake a major reorganization of their current concepts or to replace one set of central concepts with another? Even in a major conceptual reorganization, however, not all concepts are replaced. Individuals will retain many of their current concepts, some of which will function to guide the process of conceptual change. One can then ask what kinds of concepts tend to govern the process of accommodation. This is, in effect, to ask for the features of the conceptual ecologies which govern the process of major conceptual changes. We thus express our theory of accommodation in response to two questions:

1) Under what conditions does one central concept come to be replaced by another?

2) What are the features of a conceptual ecology which govern the selection of new concepts?

Conditions of Accommodation

The views of science on which this work is based differ from their empiricist predecessors in ways that are suggestive concerning the conditions of accommodation. Most varieties of empiricism tend to see the grounds for accepting a given scientific theory as the capacity of the theory to generate confirmed predictions. More recent views, however, suggest that an adequate view of the grounds for accepting a new theory must take into account the character of the problems generated by its predecessor and the nature of the new theory's competition.

One rather common theme in recent literature is that central concepts rarely directly entail anything about experience. Rather they suggest strategies and procedures whereby phenomena may be assimilated. Central concepts are thus not judged in terms of their immediate capacity to generate correct predictions. They are judged in terms of their resources for solving current problems. In Lakatos' terms (1970) research programs are not confirmed or refuted. Instead they are progressive or degenerative. Central concepts are likely to be rejected when they have generated a class of problems which they appear to lack the capacity to solve. A competing view will be accepted when it appears to have the potential to solve these problems and to generate a fruitful line of further research.

It is also important to note that a person's central concepts are the vehicle whereby a given range of phenomena become intelligible. Such concepts can be linked to prior

[5] We understand this view in direct opposition to traditional empiricism. Empiricism's central commitment that there is nothing in the mind not first in the senses, requires people to be able to learn something in the total absence of any prior concepts. We believe this to be impossible. A mind which began as a blank tablet would remain so, for it would lack the means to investigate experience.

experience, images, or models which make them appear intuitively obvious and which make competing concepts seem not just wrong but virtually unintelligible. Often, therefore, the first hurdle a set of central concepts must face in gaining acceptance is to appear to make sense.

These kinds of considerations suggest that there are several important conditions which must be fulfilled before an accommodation is likely to occur. The following four seem to us to express conditions which are common to most cases of accommodation.

1) *There must be dissatisfaction with existing conceptions.* Scientists and students are unlikely to make major changes in their concepts until they believe that less radical changes will not work. Thus, before an accommodation will occur, it is reasonable to suppose that an individual must have collected a store of unsolved puzzles or anomalies and lost faith in the capacity of his current concepts to solve these problems.[6]

2) *A new conception must be intelligible.* The individual must be able to grasp how experience can be structured by a new concept sufficiently to explore the possibilities inherent in it. Writers often stress the importance of analogies and metaphors in lending initial meaning and intelligibility to new concepts (Ortony, 1975; Belth, 1977; Black, 1962).

3) *A new conception must appear initially plausible.* Any new concept adopted must at least appear to have the capacity to solve the problems generated by its predecessors. Otherwise it will not appear a plausible choice. Plausibility is also a result of consistency of the concepts with other knowledge. A new idea in, say, astronomy is less likely to be accepted if it is inconsistent with current physical knowledge or if it simply has no clear physical account. Physical scientists prior to the 20th century, for example, were reluctant to accept what geologists were claiming about the age of the world since they had no theory which would allow the sum to provide energy for that period of time.

4) *A new concept should suggest the possibility of a fruitful research program.* It should have the potential to be extended, to open up new areas of inquiry.

Features of a Conceptual Ecology

An individual's current concepts, his conceptual ecology, will influence the selection of a new central concept. The literature in philosophy of science and our own work (to be discussed shortly) have suggested that the following kinds of concepts are particularly important determinants of the direction of an accommodation.

1) *Anomalies:* The character of the specific failures of a given idea are an important part of the ecology which selects its successor.

2) *Analogies and metaphors:* These can serve to suggest new ideas and to make them intelligible.

[6] There is, of course, a sizeable body of literature in both psychology (Smedslund, 1961; Kuhn, 1972; Berlyne, 1965) and science education (Driver, 1973; Stavy & Berkowitz, 1980) on the use of conceptual or cognitive conflict for the development of thought and conceptual change. But most of this literature has been conducted within a strictly Piagetian framework [though Berlyne (1965) reviews the broader use of conflict situations in education]. However, none of this work appears to be grounded in a theory of conceptual change of the sort discussed in this article. That is, none is focused on fundamental changes in a person's central, organizing concepts from one set of concepts to another set incompatible with the first.

3) *Epistemological commitments:*

a) Explanatory ideals: Most fields have some subject matter-specific views concerning what counts as a successful explanation in the field.

b) General views about the character of knowledge: Some standards for successful knowledge such as elegance, economy, parsimony, and not being *ad hoc* seem subject matter neutral.

4) *Metaphysical beliefs and concepts:*

a) Metaphysicial beliefs about science: Beliefs concerning the extent of orderliness, symmetry, or nonrandomness of the universe are often important in scientific work and can result in epistemological views which in turn can select or reject particular kinds of explanations. Such beliefs played a large role in Einstein's thought. Beliefs about the relations between science and commonplace experience are also important here.

b) Metaphysical concepts of science: Specific scientific concepts often have a metaphysical quality in that they are beliefs about the ultimate nature of the universe and are immune from direct empirical refutation. A belief in absolute space or time is an example.

5) *Other knowledge:*

a) Knowledge in other fields.

b) Competing concepts: One condition for the selection of a new concept is that it should appear to have more promise than its competitors.

We will see in this study how these five features of a conceptual ecology relate to the four conditions of a conceptual change in accounting for the difficulties students face in learning science. We thus turn to a study of the conceptual change required of physics students in the context of a specific topic: Einstein's special theory of relativity. This topic was chosen because it has been commonly viewed as a prototype of a scientific revolution.

The Method

In order to study students' attempts in coming to terms with the special theory, we conducted interviews in a noncalculus, self-study, self-paced introductory college physics course with students who had completed a unit on special relativity, and with several physics instructors. In the interviews, two problems were presented to the interviewees who were requested to solve the problems while thinking aloud. At each stage they were asked to give reasons for their answers, but no attempts were made to teach them in those cases where their answers were inconsistent with the special theory. The first problem considered the workings of a light clock and the implications it has for the concept of time. The second problem involved simultaneity and the synchronization of distant clocks and was followed by the presentation of written explanations from two different points of view which the interviewee was asked to read, and subsequently to repeat back, as a comprehension exercise.[7]

[7] See Posner et al. (1979) for a full description of the problems.

The Theory with Illustrations from Interviews

We now explore in greater detail the conditions governing assimilation and accommodation by relating them to the different features of a conceptual ecology listed above. The application to the special theory of relativity is illuminated by examples taken from the interviews with physics students and instructors.

Intelligibility of a New Conception

In order for a student to consider an alternative conception, he must find it intelligible. It should be clear that intelligibility is necessary for but not equivalent to or sufficient for accommodation. Intelligibility at a superficial level requires an understanding of the component terms and symbols used and the syntax of the mode of expression. For some new conceptions, this aspect of intelligibility is easily met. The special theory is one such case in which this aspect is not particularly problematic for college students with an adequate background in algebra.

However, as recent research on language comprehension demonstrates, finding discourse (or for that matter, theories) intelligible requires more than just knowing what the words and symbols mean. Intelligibility also requires constructing or identifying a coherent representation of what a passage or theory is saying (Bransford & Johnson, 1973). In fact, we would claim that no theory can function psychologically at all unless it is internally represented by the individual.

In general, representations may be in the form of propositions or images, or networks of interrelated propositions and/or images. One might, for example, represent travel distances between New York State cities as a series: Ithaca-Albany, 165 miles; Albany-Syracuse, 60 miles; Albany-New York City, 150 miles, etc. Or, the same information could be represented by a matrix formed by writing each city on both the horizontal and vertical axes of the matrix, where each matrix cell contains the distance between the two cities intersecting at the cell. Or, the same information could be represented even more economically by a New York State map with lines connecting pairs of cities and distance written on each line. Similarly, a truth table and a Venn diagram can represent the same information as propositions and as images, respectively.[8]

Representations function both passively and actively. They function passively as a format into which information must be fit. In paragraph comprehension tasks, for example, anomalous sentences are confusing (i.e., unintelligible) because they cannot be fit into the representations being built and, thus, are not easily entered into the reader's memory (Bransford & Johnson, 1973). Representations also function actively as a plan for directing one's attention and conducting purposeful searches (Neisser, 1976). The inability of readers to remember an anomalous sentence in an otherwise coherent paragraph may be attributed to the readers' inattention to it.

The different functions of a representation showed up dramatically in the comparison between the responses of a student, ON facing relativity for the first time, and an instructor, ET, who had taught physics, but not relativity, for a number of years. Both read the written explanation of the simultaneity problem, part of which follows:

When E passed A, they both set their clocks to zero and sent me a synchronization signal. Since I was a distance d_{AB}/c from A when the signal arrived I set my clock to read $t = d_{AB}/c$. So E's

[8] These examples were all adapted from Jerome Bruner (1966).

clock and my clock were correctly synchronized when E was at A, but since moving clocks run slow, when E reached me, his clock had fallen behind mine.

ON's recollection of this section came without hesitation as follows:

(B said) that when E reached point A, they synchronized the clocks to read zero, and at that point he sends a signal to B, and B synchronized his clock with t equal to the distance AB over the velocity and that's how B stated that he did it—because moving clocks run slow, E was behind.

There was no indication of any active functioning. She was intent on giving the written explanation without comment. She had already attempted her own solution to the problem, but there is no comparison between the written explanation and her own previous attempt. This, in contrast, is ET's recollection of precisely the same section:

(E said) that he sent a synchronization signal to B, and that differs from approach which was to have B look at them visually. And apparently here's B considering that (E) sent out a synchronization signal and that the distance that it travelled (pause) yes, see, that's where he's getting his velocity, relative velocity.

The representation which ET builds, functions actively to direct his attention in commenting on the written explanation and to conduct a search for any information which could be used to clear up difficulties in his own solution to the problem. As he says later:

Look, I don't remember what he said. I wasn't really trying to recall it, but to sort out my own ideas . . . I suppose I was selective in my reading, trying only to take from (the written explanation) what would clarify my own ideas.

How one represents knowledge and theories determines one's ability to make sense of and use the new ideas. Only if the student can psychologically construct a coherent, meaningful representation of a theory can it become an object of assessment and a tool of thought. Only an intelligible theory can be a candidate for a new conception in a conceptual change.

How difficult is this task for special relativity? Einstein (1954) describes the two basic postulates of special relativity as follows:

. . . Every universal law of nature which is valid in relation to a coordinate system C, must also be valid, as it stands, in relation to a coordinate system C′, which is in uniform translatory motion relatively to C . . .

The second principle, on which the special theory of relativity rests, is the "principle of the constant velocity of light *in vacuo*." This principle asserts that light *in vacuo* always has a definite velocity of propagation (independent of the state of motion of the observer or of the source of the light) (pp. 224–225).

Constructing a coherent representation of the theory's two postulates individually is not particularly problematic. One can imagine a state of affairs in which each in turn is true, although the more one accepts Newtonian mechanics the harder it will be to imagine a world in which the postulate about constancy of the speed of light is true. But in balance, intelligibility of each of Einstein's two postulates is not particularly problematic.

The intelligibility of the theory as a whole, however, is a different matter. Finding it intelligible entails imagining a world in which both of Einstein's postulates are true, together with the logical implications of the postulates for notions of space and time. This task is a demanding one. To make matters even more difficult, it is possible to apply the postulates and formulas of special relativity in a superficial way without those necessary revisions in one's conceptions of space and time which are in accord with the theory; or without even having understood the full implications of its principles. Thus, both learner and instructor can mistake the intelligibility of the parts—the postulates of the special theory—for the intelligibility of the whole.

Initial Plausibility of a New Conception

One source of difficulty in learning special relativity stems from its lack of initial plausibility to physics students. Regardless of how intelligible one finds the theory, it may still appear counterintuitive. What makes a theory like special relativity counterintuitive?

Initial plausibility can be thought of as the anticipated degree of fit of a new conception into an existing conceptual ecology. There appear to be at least five ways by which a conception can become initially plausible.

1) One finds it consistent with one's current metaphysical beliefs and epistemological commitments, i.e., one's fundamental assumptions.

2) One finds the conception to be consistent with other theories or knowledge.

3) One finds the conception to be consistent with past experience.

4) One finds or can create images for the conception, which match one's sense of what the world is or could be like.

5) One finds the new conception capable of solving problems of which one is aware (i.e., resolving anomalies).[9]

Of these five factors the first appears to offer the greatest explanatory power with regard to the difficulties faced by students attempting to learn Einstein's special theory. Let us then look at fundamental assumptions as they bear on this learning task.

One set of fundamental assumptions is the individuals' epistemological commitments. Einstein (1949) was committed to two fundamental epistemological principles:

1) A theory must not contradict empirical facts; and

2) The premises of the theory must be characterized by "naturalness" or "logical simplicity," a kind of "inner perfection" of the theory. He was committed so fully to these two principles that he was able to apply them ruthlessly, even if that application meant a rejection of our common sense notions of space and time.

Needless to say, students do not always share Einstein's epistemological commitments, but their own commitments are likely to be highly significant in determining what they find initially plausible and, thus, in shaping their conceptual changes. Therefore, it is important to find out just what epistemological commitments students have, if one wants to understand what they are likely to find initially plausible or implausible and more generally, to understand their processes of conceptual change. What is their theory of theories? What is their theory of knowing? What is their view of the relation of disciplinary knowledge to everyday knowledge?

[9] The present discussion will focus only on the first of these five ways, that is, on the individual's fundamental assumptions. In the next section we elaborate on the last of these ways. There we discuss the dual function of anomalies.

Scientific metaphysical beliefs, like epistemological commitments, are central to a conception. The central scientific metaphysical belief that contrasts special relativity with its immediate predecessors is its rejection of an absolute space and absolute time in favor of an interpretation which considers space and time relative to any given inertial system. So long as students are firmly committed to absolute space and time, they will find the special theory counterintuitive.

A good example of such a commitment is provided by student CP, who outlines her belief in absolute time explicitly and repeatedly. In response to a portion of the simultaneity problem (for which the special theory predicts that two clocks read different times) she responds:

(CP) I mean, how could they change? Time only goes at one rate, right?

After she has read the written explanation showing the derivation of the relativistic prediction, the interviewer (I) questions her further:

(I) And so what about this idea of absolute time?

(CP) I can't say that's *not* true . . .

CP not only states her belief in absolute time but at a later stage shows how she defends it in a discussion of the troublesome results of the simultaneity problem which she assimilates into an existing conception:

(I) I'm just asking you what you feel about results like that.

(CP) Yeah, I mean, absolute time, it just seems to go on at a certain rate everywhere. It just seems natural that it's constant everywhere. I mean, even though you see these results.

(I) . . . it seems these are strange results. What attitude do you take of these results?

(CP) I say they don't really mean all that much; it just depends on what your frame is. It's sort of like potential energy depends on the way you define zero to be?

(I) The amount of potential energy you've got?

(CP) Right, all relative to what's going on.

CP's reference to potential energy is significant in pinpointing a conception which enables her to regard the values given to a variable as arbitrary, being dependent solely on the observer's point of view. She attempts to resolve some counterintuitive results of Einstein's view of time by drawing an analogy between time and potential energy. No matter that the analogy might break down with further analysis—it serves her belief in absolute time.

It is appropriate at this point to note the importance of the strength and depth of a metaphysical belief in determining whether assimilation or accommodation occurs. Because CP's commitment to absolute time is so strong, accommodation is a less attractive option than assimilation, and as a result she needs to be able to make her belief in absolute time and her understanding of special relativity consistent. She succeeds, to her satisfaction, by using the potential energy analogy.

A tutor in the course, SL, provides another example of an attempt to assimilate the findings of the special theory into an existing conception, in this case in a rather more sophisticated and detailed fashion. He shows a firm Newtonian commitment to a mechanistic view of the world which requires that objects have fixed properties such as length, mass, etc., and that explanations of phenomena should be given in terms of these objects and their interactions. In talking about the question of shrinking rods and slowing clocks, he says:

(SL) I see them as being—as changing their length, or changing their time. But I can't talk to the person who's moving at the same velocity as the stick and the clock. He's telling me that they don't change . . . I feel they haven't changed, but the way I'm looking at them has changed . . . I guess I'm allowing for the fact that person who's seeing these things at rest, who has his clock at rest, his meter stick at rest, has (pause) a little more right to say what is really happening to the sticks.

A little later he continues:

(SL) But I'm not at all uncomfortable with the idea of foreshortening. I do say, I do feel it is a perception. I will say it is a shortening. I know in the back of my mind that my friend who's riding along with that meter stick is telling me all the time that as far as he can tell, it's the same length and I believe what he's saying, which is o.k.

(I) It's not a conflict?

(SL) No, because the fact that it's moving makes it appear to me as if it were foreshortened.

Here SL insists on treating length as constant, independent of frames of reference. He is, thus, led to treat the special theory's claims concerning the relativity of length as simply a distortion of perception.

What is of interest to us at this point is that SL reveals this commitment by using it as the conception to which he assimilates the findings of special relativity. In order to do this he has to make two auxiliary assumptions: that a shrinking rod constitutes a perceptual problem, and doesn't actually shrink ("I feel they [rods and clocks] haven't changed, but the way I'm looking at them has changed"), and that in principle a mechanistic interpretation in terms of objects and their motion is needed in order to explain why clocks run slower ("I don't see how in depth . . . but I believe it can be done"). Neither of these assumptions is necessary or even consistent with an Einsteinian perspective based on a reanalysis of space and time. They do, however, play an integral part in protecting SL's metaphysical commitments.

Dissatisfaction with Existing Conceptions[10]

Generally, a new conception is unlikely to displace an old one, unless the old one encounters difficulties,[11] and a new intelligible and initially plausible conception is available that resolves these difficulties. That is, the individual must first view an existing conception with some dissatisfaction before he will seriously consider a new one.

One major source of dissatisfaction is the anomaly. Each time a person unsuccessfully attempts to assimilate an experience or a new conception into his existing network of conceptions, that person experiences an anomaly. An anomaly exists when one is unable to assimilate something that is presumed assimilable—or (in other words), one simply cannot make sense of something.

[10] The reader should note that this section builds on some of the points raised in the two previous sections. Therefore, for purposes of clarity and succinctness, this section is placed out of order in relation to the list of conditions presented earlier.

[11] Lakatos (1970) terms these difficulties "recalcitrant data."

When faced with an anomaly, the individual (scientist or student) has several alternatives. One may come to the conclusion that one's existing conceptions require some fundamental revisions (i.e., an accommodation) in order to eliminate the conflict. But this is the most difficult and, therefore, the most unlikely approach, especially when there are other possibilities:

1) rejection of the observational theory[12];
2) a lack of concern with experimental findings on the grounds that they are irrelevant to one's current conception;
3) a compartmentalization of knowledge to prevent the new information from conflicting with existing belief ("Science doesn't have anything to do with the 'real' world"); and
4) an attempt to assimilate the new information into existing conceptions (e.g., "Newtonizing" relativistic phenomena).

This analysis suggests that the presentation of anomalies will produce dissatisfaction with an existing conception only if:

1) Students understand why the experimental finding represents an anomaly;
2) Students believe that it is necessary to reconcile the findings with their existing conceptions;
3) Students are committed to the reduction of inconsistencies among the beliefs they hold; and
4) Attempts to assimilate the findings into the students' existing conceptions are seen not to work.

Given the improbability that all these conditions will be met, it is no wonder that few students find their current conceptions weakened by anomalies. Why consider alternatives to a Newtonian view (or whatever view they hold) when they are unconvinced of the inadequacy of their conceptions? The search for instructionally viable and effective anomalies is of primary importance if accommodation is to be taken seriously as a goal. Recounting historical anomalies (such as the Michelson-Morley experiment) won't always do!

Assuming this formidable instructional problem is solved, the process of accommodation can proceed. If the dissatisfaction with the existing conception created by its inability to make sense of experience is followed by learning of an intelligible alternative which resolves or promises to resolve some of the anomalies of its predecessor, then the new conception may be plausible.

There is little evidence in the interviews that students were aware of anomalies, even though videotapes of two experiments formed part of the study material in the course. It is significant that the clearest example of a student's awareness of anomalous behavior occurs along with a statement of his epistemological commitment.

HU has derived a mistaken result from his view of the relativity principle which implies that pictures taken by two cameras moving past one another at the same instant and of

[12] Reports of observation are not theory neutral. Rather, observations are described and interpreted by means of concepts taken from some theory, or some theory is assumed in treating the observations as data. Treating observations of the red shift as a measure of distance assumes a wave theory of light and, in some cases, relativity. Even the use of a telescope assumes a theory of optics. Theories which function to describe or interpret data we refer to as observation theories.

the same two clocks will show different things. The interviewer looks for confirmation of this view:

(I) So what you're saying is that they wouldn't agree, they couldn't agree, that they'd actually see different things.

(HU) Right.

(I) That doesn't bother you?

(HU) It did at first, but when you think about it and hash it out, there really is no reason why we should limit ourselves to one frame of mind. I like to think abstractly and I can see that. I had trouble realizing that lengths would change, too, but you know, I'm game! No, it doesn't bother me. It's just that we don't realize it due to our slow speeds. I tend to agree with scientific data that's brought up and when they say that an electron—what was that—a meson, actually goes with the predictions, what can you do? And once you see the facts, you can stretch your imagination.

HU's stated epistemology is simple and empiricist: Theories are derived from experimental evidence. It also appears to exhibit a degree of tolerance for theoretical inconsistencies, which tolerance precludes him from seeing that he has made a mistake. However, HU has pinpointed one anomaly: Newtonian mechanics calculates the lifetime of a meson to be much shorter than that which is observed experimentally. He has, however, seen that special relativity's prediction agrees with experiment. Thus, HU sees an anomaly, he sees the alternative conception, and his epistemological commitment allows for its plausibility.

Fruitfulness of a New Conception

Once aware of an intelligible, plausible alternative to an existing conception that resolves apparent anomalies, students may actively attempt to map their new conceptions onto the world; that is, they may attempt to interpret experience with it. If the new conception not only resolves its predecessor's anomalies but also leads to new insights and discoveries, then the new conception will appear fruitful and the accommodation of it will seem persuasive.

A brief examination of the fruitfulness of the special theory for professional scientists may suggest some of the theory's potential. It is this potential of which students should be made aware, if they are to share in the view that the theory is indeed fruitful, and, thus, worth accommodating:

1) As an engineering tool in the design of accelerators (relativistic mechanics);

2) As a technological tool in the development of nuclear weapons and nuclear reactors;

3) As a theoretical and technological tool in nuclear chemistry for predicting the products of nuclear reactions;

4) As a theoretical and mathematical tool in astronomy for calculating life expectancies of stars, for explaining astronomical phenomena (e.g. supernovae), and for making calculations of astronomical distances;

5) As a theoretical basis (along with quantum physics) for the development of modern physics.

To the extent that the student can understand these contributions and trace them back to the basic postulates of the special theory, they may begin to appreciate the fruitfulness of the theory.

The Character of Accommodation

Our description of the four conditions of a successful accommodation may have suggested a fairly straightforward linear process: students' dissatisfaction with Newtonian physics; followed by the students' finding special relativity intelligible: leading to an initial belief in its plausibility; and concluding with the belief that the theory is ultimately fruitful.

However, it should be clear that this account is oversimplified, since many basic conceptions, including relativity, are so complex that at a particular time one is likely to accommodate certain aspects but not others. We have, of course, described accommodation as a radical change in a person's conceptual system. That an accommodation is a radical change does not, however, entail that it is abrupt. Indeed, there are good reasons to suppose that for students accommodation will be a gradual and piecemeal affair. Students are unlikely to have at the outset a clear or well-developed grasp of any given theory and what it entails about the world. For them, accommodation may be a process of taking an initial step toward a new conception by accepting some of its claims and then gradually modifying other ideas, as they more fully realize the meaning and implication of these new commitments. Accommodation, particularly for the novice, is best thought of as a gradual adjustment in one's conception, each new adjustment laying the groundwork for further adjustments but where the end result is a substantial reorganization or change in one's central concepts.

Our interviews also indicate that what may initially appear as an accommodation may turn out to be something less than that. As the interview with SL indicates, people who accept Einstein's two postulates may understand them in a rather non-Einsteinian fashion. Often it appears that as students, who have accepted the two postulates, begin to realize their counterintuitive implications or their conflicts with Newtonian notions of space and time, the commitment to the two postulates weakens. Typically, students will attempt various strategies to escape the full implication of the two postulates or to reconcile them with Newtonian assumptions. Accommodation may, thus, have to wait until some unfruitful attempts at assimilation are worked through. It rarely seems characterized by either a flash of insight, in which old ideas fall away to be replaced by new visions, or as a steady logical progression from one commitment to another. Rather, it involves much fumbling about, many false starts and mistakes, and frequent reversals of direction.

Educational Implications

Teaching science involves providing a rational basis for a conceptual change. We have also seen that fundamental conceptual changes, termed accommodations, may involve changes in one's fundamental assumptions about the world, about knowledge, and about knowing and that such changes can be strenuous and potentially threatening, particularly when the individual is firmly committed to prior assumptions. We have seen that people resist making such changes, unless they are dissatisfied with their current concepts and find an intelligible and plausible alternative that appears fruitful for further inquiry.

Two features of a conceptual ecology, in particular, were shown to guide the change process from one conception to another: 1) anomalies, and 2) fundamental assumptions about science and about knowledge.

If taken seriously by students, anomalies provide the sort of cognitive conflict (like a Kuhnian state of "crisis") that prepares the student's conceptual ecology for an accommodation. The more students consider the anomaly to be serious, the more dissatisfied they will be with current concepts, and the more likely they may be ready ultimately to accommodate new ones.

Metaphysical beliefs and epistemological commitments form the basis on which judgments are made about new knowledge. Thus, a conceptual change will be rational to the extent that students have at their disposal the requisite standards of judgment necessary for the change. If a change to special relativity requires a commitment to the parsimony and symmetry of physical theories (as it did for Einstein), then students without these commitments will have no rational basis for such a change. Faced with such a situation students, if they are to accept the theory, will be forced to do so on nonrational bases, for example, because the book or the instructors says it is "true."

Our study of the history of science reveals that many conceptual changes in science have been driven by the scientists' fundamental assumptions rather than by the awareness of empirical anomalies.[13] Einstein's special relativity can be seen as such a case.[14] However, since it is unlikely that students in an introductory physics course can be successfully taught the requisite standards of judgment for an accommodation of special relativity, physics teachers must rely on "anomalies" to prepare the student for the accommodation.

Our problem remains unsolved, however. Most of the anomalies will not be readily seen as anomalies by students without a thorough understanding of the observational theory in which the experiment was embedded. That is, most of the experiments are far from being "transparent." Does this problem mean that the special theory can realistically be made at best only intelligible and partially plausible, but never fully persuasive tc students who are firmly committed to a set of conflicting metaphysical beliefs and epistemological commitments? It is one thing to educate physicists over a course of four tc six years into a given set of standards of judgment. It is quite another thing to accomplish this goal in an introductory physics course, along with covering a great deal of content And further, how is one to demonstrate the theory's fruitfulness in the limited time available?

Accepting, then, that accommodation of the special theory runs the risk of being difficult if not impossible, is there anything we as educators can do to enable physics student to accommodate new conceptions on a rational basis? Let us examine the implication of our research for science education. We shall frame these implications in the form o questions and suggestions raised by our research thus far.

Curricular Objectives

Our discussion of the critical role played by the student's fundamental assumption about the world and about their knowledge of the world raises serious questions abou the objectives of science courses. If the conceptual change process is to be rationally base then students will need to be immunized against the kind of inevitable indoctrinatic

[13] See Burtt's (1962, pp. 36–62) account of Copernicus, whose theory was not a response to anomalies, bu was only presented as a simpler and more harmonious interpretation.

[14] Empirical findings anomalous with respect to Newtonian physics but consistent with Einsteinian theor developed many years after the special theory of relativity was proposed.

that occurs when neither the teacher nor the student is aware of his own fundamental assumptions, much less those implied by the science he is teaching and learning.

The primary question which must be raised about curriculum objectives as a result of our discussion in this article is the following: Is it realistic to expect science instruction to produce accommodation in students, rather than merely to help students make sense of new theories? And secondarily, should this be an expectation for all students, or only for certain groups, such as science majors?

In the event that an affirmative answer is given to the primary question, the contents of the previous sections suggest we aim at developing in students:

1) An awareness of their fundamental assumptions and of those implicit in scientific theory;

2) A demand for consistency among their beliefs about the world;

3) An awareness of the epistemological and historical foundations of modern science;

4) Some sense of the fruitfulness of new conceptions.

The extent to which any of the above should be considered is a matter for future investigation.

Content

If we aim to produce rationally based conceptual change in students, then according to what we have said thus far, the content of science courses should be such that it renders scientific theory intelligible, plausible, and fruitful. In order to give expression to this general requirement, the following conditions appear to be necessary:

1) More emphasis should be given to assimilation and accommodation by students of that content than to content "coverage."

2) "Retrospective anomalies" should be included, particularly if historically valid anomalies are difficult to comprehend, or, as with the special theory, were not responsible for driving the conceptual change in the first place.[15]

3) Sufficient observational theory should be taught for students to understand the anomalies employed.

4) Any available metaphors, models, and analogies should be used to make a new conception more intelligible and plausible.

Teaching Strategies

Teaching is typically thought of as clarifying content presented in texts, explaining solutions to problems, demonstrating principles, providing laboratory exercises, and testing for recall of facts and ability to apply knowledge to problems. That is, teaching is for recall and assimilation. For teaching aimed at accommodation the following possible changes in this approach are implied by our research:

1) Develop lectures, demonstrations, problems, and labs which can be used to create cognitive conflicts in students. Among other things, one might consider what types of homework problems would create the kind of cognitive conflict necessary as preparation for an accommodation, and whether labs could be used to help students experience anomalies (Stavy & Berkowitz, 1980).

[15] See Anthony P. French (1968, pp. 6-29), for an example of the use of retrospective anomalies in teaching special relativity.

2) Organize instruction so that teachers can spend a substantial portion of their time in diagnosing errors in student thinking and identifying defensive moves used by students to resist accommodation.

3) Develop the kinds of strategies which teachers could include in their repertoire to deal with student errors and moves that interfere with accommodation.

4) Help students make sense of science content by representing content in multiple modes (e.g., verbal, mathematical, concrete-practical, pictorial), and by helping students translate from one mode of representation to another (Clement, 1977).

5) Develop evaluation techniques to help the teacher track the process of conceptual change in students (e.g., the Piagetian clinical interview) (Posner & Gertzog, 1982).

Teacher Role

The teacher as clarifier of ideas and presenter of information is clearly not adequate for helping students accommodate new conceptions. Our research suggests that the teacher might have to assume two further roles in order to facilitate student accommodation. In these roles the teacher would become:

1) An adversary in the sense of a Socratic tutor. In this role, the teacher confronts the students with the problem arising from their attempts to assimilate new conceptions. (A point of concern is the need to avoid establishing an adversarial role with regard to students as persons while developing and maintaining it with regard to conceptions.)

2) A model of scientific thinking. Aspects of such a model might include a ruthless demand for consistency among beliefs and between theory and empirical evidence, a pursuit of parsimony among beliefs, a skepticism for excessive "*ad hoc*-ness" in theories and a critical appreciation of whether discrepancies between results may be in "reasonable agreement" with theory.[16]

Whether any of the above changes could be implemented, and the extent to which they would prove effective in facilitating accommodation in students, are questions which we have not as yet addressed.

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[16] See Thomas S. Kuhn (1977, pp. 178–224), for an insightful discussion of this point. For a useful discussion of the teacher as a model of scientific thought, see Gene D'Amour (1977, pp. 183–190).

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