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Abstract

Understanding how science students respond to anomalous data is essential to understanding knowledge acquisition in science classrooms. In this report, we present a detailed analysis of the ways in which scientists and science students respond to anomalous data. We postulate that there are seven distinct forms of response to anomalous data, only one of which is to accept the data and change theories. The other six responses involve discounting the data in various ways in order to protect the preinstructional theory. We analyze the factors that influence which of these seven forms of response a scientist or student will choose, giving special attention to the factors that make theory change more likely. Finally, we discuss the implications of our framework for science instruction.

THE ROLE OF ANOMALOUS DATA IN KNOWLEDGE ACQUISITION: A THEORETICAL FRAMEWORK AND IMPLICATIONS FOR SCIENCE INSTRUCTION

This report addresses an issue that is crucial for understanding how people learn science and how to improve science instruction: How do students respond when they encounter scientific information that contradicts their current theories[1] about the physical world? In other words, how do students respond when their current beliefs about the physical world conflict with the information presented during science instruction?

This issue is crucial for two reasons. The first is that encountering contradictory information is a very common occurrence when one is learning science. Science students' preinstructional beliefs about the natural world often conflict sharply with many of the accepted scientific theories they are taught in school, and this is true across a wide variety of domains within biology, chemistry, and physics (for reviews, see Carey, 1985; Champagne, Klopfer, & Gunstone, 1982; Confrey, 1990; Driver & Easley, 1978; Driver, Guesne, & Tiberghien, 1985; Eylon & Linn, 1988; Osborne & Freyberg, 1985; Perkins & Simmons, 1988; Roth, 1990). Thus, the encounter with contradictory information is at the heart of knowledge acquisition in science.

The second reason why understanding how students respond to contradictory information is crucial for science education is that students typically resist giving up their preinstructional beliefs. Instead of abandoning or modifying their preinstructional beliefs in the face of new, conflicting data and ideas, students often staunchly maintain old ideas and reject or distort new ideas. For instance, some children who are told that the earth is round preserve their preinstructional belief that the earth is flat by concluding that the earth is disc shaped (Vosniadou & Brewer, 1992). Similarly, children can spend days or weeks studying photosynthesis and yet persist in their preinstructional belief that plants get their food from the soil (Anderson & Smith, 1984). And a number of researchers have found that many young adults go through high school and university physics courses without ever giving up their pre-Newtonian views of motion (e.g., Champagne, Klopfer, & Anderson, 1980; Clement, 1982; McCloskey, Caramazza, & Green, 1980). It is clear that a key to improved science education is to find better ways of convincing students to change their preinstructional theories in response to new, contradictory scientific ideas.

The Role of Anomalous Data

The current literature on science education includes many new instructional approaches that take students' preinstructional theories into account and are designed to convince students to change their theories. Virtually all of these approaches share one key ingredient: the use of *anomalous data*, that is, presenting students with evidence that contradicts their preinstructional theories. The anomalous data are intended to cause students to become dissatisfied with their current theories, which cannot account for the anomalous data, and to adopt instead the target scientific theory, which successfully explains the data (e.g., Posner, Strike, Hewson, & Gertzog, 1982). Educational researchers who have advocated using anomalous data to spur students to change their preinstructional theories include Alvermann and Hynd (1989); Anderson (1977); Brown and Clement (1992); Champagne, Gunstone, and Klopfer (1985); Collins (1977); diSessa (1982); Dreyfus, Jungwirth, and Eliovitch (1990); Finegold and Gorsky (1988); Hewson and Hewson (1983); Hewson (1981); Inagaki (1981); Johsua and Dupin (1987); Minstrell (1989); Neale, Smith, and Johnson (1990); Nussbaum and Novick (1982); Pines and West (1986); Posner et al. (1982); Roth (1990); Roth, Anderson, and Smith (1987); Rowell and Dawson (1983); Wang and Andre (1991); Watson and Konicek (1990); and White and Frederiksen (1990). The particulars of these approaches vary widely, and the anomalous evidence itself is presented in different ways, sometimes through laboratory work or live demonstrations, sometimes through computers, and sometimes through discussions. Regardless of the details of the method, the presentation of anomalous data is always a key step intended to precipitate theory change.

We agree that presenting students with anomalous data is a promising instructional technique. In the history of science, anomalous data have played an important role in scientific revolutions (Humphreys, 1968; Kuhn, 1962), and it is plausible to assume that persuasive data are needed to convince students to abandon well-entrenched preinstructional theories. But the use of anomalous data is no panacea. Science students frequently react to anomalous data by discounting the data in some way, thus preserving their preinstructional theories. For example, Champagne et al. (1985) report a study in which students who believed that heavy objects fall faster than light objects subsequently watched the teacher attempt to refute their belief by dropping two blocks of different weights from a common height. Although the blocks appeared to strike the ground simultaneously, many students refused to accept the anomalous data. Two middle school students "reasoned that the blocks had, in fact, fallen at different rates, but that the difference in descent times was too small to be observed over the short distance (approximately one meter) used in the original demonstration" (p. 65). Other students declared that the blocks must, in fact, have been of equal weight. Thus, anomalous data do not always lead to belief change. Students often find ways to discredit anomalous data and protect their preinstructional beliefs against the data.

Core Questions

To use anomalous data in science instruction, educators must gain a better understanding of how students deal with data that contradict their preinstructional theories. In order to use anomalous data effectively in instruction, it is necessary to know the answers to three questions:

1. What are the different responses a student can make to anomalous data?

2. What are the conditions that lead to different responses to anomalous data? That is, why does a student ignore anomalous data in one instance, reject anomalous data in another instance, and abandon his or her preinstructional theory in a third instance?

3. Drawing on the answers to the first two questions, what can educators do to make theory change more likely in the classroom? How can instruction be designed to make theory change more likely and to make the discrediting of anomalous data less likely?

The purpose of this report is to suggest answers to these three questions. We propose a theoretical framework for understanding *how* students respond to contradictory data and *why* they respond as they do. Then we use this framework to make recommendations for science instruction.

Although the issue of how scientists and science students respond to anomalous information is critical for science education, no one, to our knowledge, has yet developed a detailed framework for understanding responses to anomalous information. Several researchers, such as Hewson (1981) and Schank, Collins, and Hunter (1986), have listed some ways in which people may react to anomalous information, and many relevant insights are scattered throughout Thomas Kuhn's (1962) *The Structure of Scientific Revolutions*. Other relevant observations are dispersed widely in the literatures on the history of science, philosophy of science, science education, cognitive science, cognitive psychology, developmental psychology, and social psychology.

As we have searched the literatures on the history of science and on education and psychology for instances of people responding to anomalous data, we have been struck by the similarities in the descriptions of the responses of scientists, nonscientist adults, and science students. The fundamental ways in which scientists react to anomalous data appear to be identical to the ways in which nonscientist adults and science students react to anomalous data. Thus, our analysis will provide support for the thesis that the scientific reasoning processes of children are similar to those of scientists (Brewer & Samarapungavan, 1991; Carey, 1985).

The remaining three parts of this report correspond to the three questions raised above. In the first part, we classify the forms of response to anomalous data. We discuss each postulated form of response and provide evidence for our position with examples from the history of science and from psychology and science education. In the second part, we discuss the factors that influence how people respond to anomalous data, giving particular attention to what causes a person to be convinced by the anomalous data instead of attempting to shield the pre-existing theory from change. In the third part, we discuss the implications of our analysis for science instruction.

Forms of Psychological Response to Anomalous Data

In idealized form, we conceptualize the situation in which anomalous data occur as follows: An individual currently holds theory A. The individual then encounters anomalous data, data that cannot be explained by theory A. The data may be anomalous because they clearly conflict with theory A or simply because theory A cannot be used to marshal any explanation for the data. The anomalous data may or may not be accompanied by theory B, which is intended to explain much of the body of data explained by theory A, plus the anomalous data.

What are the possible responses of the individual to the anomalous data? We postulate that there are seven basic responses: (a) *ignore* the anomalous data, (b) *reject* the data, (c) *exclude* the data from the domain of theory A, (d) hold the data in *abeyance*, (e) *reinterpret* the data while retaining theory A, (f) reinterpret the data and make *peripheral changes* to theory A, and (g) accept the data and *change* theory A, possibly in favor of theory B. We think this is close to an exhaustive set of the possible responses to anomalous data.

In the next sections, we discuss each of these forms of response to anomalous data. After that, we present a theoretical justification for choosing just these seven forms of response and for concluding that they are an exhaustive set of possible responses.

As we discuss each form of response, we will support our analysis with selected examples from the history of science and experimental evidence from psychology and science education. We have included historical examples for four reasons. First, the history and philosophy of science have been fruitful sources of ideas and evidence for science educators (e.g., Duschl & Gitomer, 1991; Snir, 1991). Second, the examples from the history of science are often particularly clear and compelling. Third, a classification that aims to account for how people respond to anomalous data about the physical world ought to be able to account for both the responses of scientists and the responses of science students. Finally, we want to illustrate the similarities between scientists and science students. When we juxtapose examples from the history of science with examples from psychology and science education, it becomes clear that science students frequently respond in the same essential ways that scientists do.

Ignoring Anomalous Data

The most extreme way to dispose of a piece of anomalous data is simply to ignore it. When an individual ignores data, he or she does not even bother to explain the data away. Theory A remains intact and totally unscathed.

History of science. The popular press frequently publishes "data" that contradict received scientific ideas, but these data are typically ignored by scientists. Thus, physicists ignore reports of new perpetual motion machines. Psychologists ignore claims for the existence of ESP. Astronomers ignore the predictions of astrology. Biologists ignore the reports of sightings of the Loch Ness monster.

However, it is not merely fringe ideas like ESP and astrology that get ignored by scientists. Data that are later accepted by the scientific community may be similarly ignored when they are first presented. An example is the reception of the meteor impact theory of mass extinctions at the end of the Cretaceous Period. In 1980, Luis Alvarez and his colleagues (Alvarez, Alvarez, Asaro, & Michel, 1980) reported that the K-T boundary in Italy (the K-T boundary is the boundary between Cretaceous and Tertiary sediments) contained an anomalously high amount of iridium and argued that the iridium could have come only from a meteor or comet; therefore, the mass extinction of species at the end of the Cretaceous period must have been caused by the impact of a meteor or comet. But at a later conference, attended by Alvarez, at which paleontologists discussed mass extinctions, there was no mention of the word *iridium*. The paleontologists ignored Alvarez's data (Muller, 1988, p. 72).

Psychology and education. In a study of middle school students reading science texts, Roth and Anderson (1988) provided evidence that students sometimes ignore information in science texts that contradicts their existing schemas. In their study, several students gleaned almost no new information from the texts; instead, they used a few key words in the text to call up a preexisting schema. One such student, Maria,

> read a section of one text that used milk as an example of how all foods can ultimately be traced back to green plants, the food producers. Maria announced that "most of this stuff I already knew."
>
> . . . "It's just about milk . . . how we get our milk from cows." In fact, the text did not discuss people at all in this example. Maria never picked up any notion of the main ideas the text was developing--that plants make food. This is typical of her pattern of reading to find familiar ideas, ignoring the rest of the text, and relying on prior knowledge to fill in the details. (Roth & Anderson, 1988, p. 114)

From this description, it is not clear whether Maria simply did not read the new information or whether she read it extremely superficially. But either behavior fits into the category of ignoring new information.

Deanna Kuhn (1989) reported a study that indicated that students may ignore data that contradict their favored causal hypothesis. As an example, one ninth-grade girl believed that eating a Mars Bar (a kind of candy bar) is unrelated to whether one catches a cold, whereas eating mustard causes one to catch a cold. Presented with a pattern of noncovariation between the type of candy bar and catching cold, the girl said, "With the Mars Bar you get a cold off and on, because here's one they got colds and over here they didn't . . . so it really doesn't matter" (p. 677). But presented with the same pattern of noncovariation for mustard, the girl interpreted the evidence very differently: "Mostly likely all the time you get a cold with the mustard. Like there you did [instance 2] and there you did [instance 7]" (p. 677, brackets in original). The girl appears to have ignored the two instances where mustard was not associated with colds. The girl's prior theory asserted that mustard causes colds, so she ignored the data that contradicted her causal hypothesis.

Rejecting Anomalous Data

Rejecting data is similar to ignoring data in that the individual does not accept the data in either case, nor does he or she make any changes to theory A. The difference is that in ignoring data, the individual does not even attempt to explain the data away; in rejection, the individual can articulate an explanation for why the data should be rejected.

Rejection is very common among scientists. It can vary from a detailed methodological or theoretical critique to a vague "There must be something wrong with the experiment." According to Richard Muller (1988), Professor of Physics at the University of California at Berkeley:

> When presented with a new, startling, and strange result, it is easy to find flaws and come up with reasons to dismiss the finding. Even if the skeptic can't find an outright mistake, he can say, "I'm not convinced." In fact, most scientists (myself included) have found that if you dismiss out of hand all claims of great new discoveries, you will be right 95% of the time. (Muller, 1988, p. 73)

By this standard, it appears that compared to scientists, science students may be remarkably open to new data!

Individuals who reject data use a wide variety of reasons for the rejection; however, three very common forms of rejection are (a) arguing that there was a fundamental methodological error in the way the data were obtained, (b) arguing that the data were merely due to random variation, and (c) declaring the data to be fraudulent.

Methodological Error

Perhaps the most common grounds for rejecting data is methodological error. The individual asserts that the procedure by which the data were collected is flawed.

History of science. One of the classic cases of rejection based on methodological error occurred when Galileo published the results of his first observations with the telescope. These observations were inconsistent with the then current Aristotelian world view. It appears that initially most astronomers and philosophers rejected the data as due to methodological artifacts introduced by the telescope itself (Drake, 1980, p. 44).

Psychology and education. Science students sometimes reject data presented in science classes on methodological grounds. Johsua and Dupin (1987) report a classroom study in which students were debating different explanatory models of a simple electrical circuit, in which a battery was connected to a light bulb. Most of the students incorrectly believed that electrical current "wears out" as it travels from a battery around the circuit. That is, these students believed that some of the current gets used up in order to light up the bulb, so that the current entering the bulb is greater than the current leaving it. The teacher attempted to refute this incorrect belief by inserting two ammeters into the circuit, one on each side of the light bulb. The ammeters showed that the current on each side of the bulb was the same. But instead of changing their beliefs, many students rejected the data on methodological grounds. They stated, for example, that "the apparatus is bust" and that "the bulb was bad, then the battery; let's change them" (p. 129).

Pickering and Monts (1982) studied undergraduates in a chemistry laboratory who, in the course of carrying out a laboratory experiment, generated data that contradicted their prior beliefs. Although their data were, in fact, correct, 45% of the subjects asserted that the data were in error and explained the data away by attributing them to methodological error. Among the subjects who stated that the data were in error, 53% offered a specific methodological explanation, and 47% offered only a vague explanation or merely asserted that there was a methodological error.

Random Error

Another form of rejection is to assert that the anomalous finding is just a random occurrence.

History of science. Wegener argued that the close fit between the east coastline of South America and the west coastline of Africa supported his theory of continental drift. However, his opponents argued that the degree of fit was simply chance (Hallam, 1973). Similarly, when Weber claimed to have found evidence for gravity waves, one of his critics stated, "By massaging data again and again, knowing what you want for an answer, you can increase the apparent statistical significance of any bump . . . I'm pretty sure he could get there out of pure noise." (Collins, 1981, p. 40)

Psychology and education. Gorman (1986, 1989) has conducted a series of studies to examine how people respond when they are told that there is a chance that the anomalous data they receive are in error. Using a rule discovery task, Gorman (1986) found that when subjects were told that there was a 20% chance that data that contradicted their hypothesis were in error, subjects often rejected the contradictory data. These subjects apparently assumed that data that contradicted their hypothesis must have been among the 20% of the data that were in error. Gorman (1986) also found that "the possibility of errors seems to make it harder for groups to abandon a rule even when they have clearly disconfirmed it" (p. 94).

Fraud

This is the most extreme form of rejection. The individual dismisses the anomalous data as a joke or as outright fraud.

History of science. When Lord Kelvin first heard about X rays, he apparently believed that the reports were a hoax (Thompson, 1976, p. 1125). Similarly, the chemist Kauffman (1988, p. 264) reports that when he first heard that Bartlett had formed a compound with one of the noble gases he assumed that the announcement was a joke.

Psychology and education. We know of no experimental studies in psychology in which subjects rejected data as a hoax. The demand characteristics of most studies appear to preclude such a response. But Hesse (1987) provides an example from science education. Hesse hung two balls of steel wool on an equal arm balance. Because the two balls had equal mass, the arm of the balance remained level. Then Hesse placed a Bunsen burner under one of the balls. Most students predicted that the heated ball would weigh less. "After the demonstration students were astonished that the heated side weighed more. Several students in disbelief claimed that I somehow rigged the balance" (p. 199).

Excluding Anomalous Data

Another possible response to contradictory data is to declare the data to be outside the domain of the theory. Suppe (1974) notes:

> Theories have as their subject matter a certain range of phenomena and they are developed for the purpose of providing answers to a variety of questions about the phenomena in that range.... The range of questions the theory is intended to answer about the phenomena is quite selective; the theory is not expected to be able to answer all possible questions which could be asked about the phenomena in its range. (p. 211)

Thomas Kuhn (1962) makes a similar generalization and notes that one response to anomaly is for scientists to treat it as "the concern of another discipline" (p. 37). Thus, one approach to anomalous data is simply to assert that one's theory is not intended to account for those data.

In contrast to the individual who rejects anomalous data, the individual who excludes data from his or her theory does not have to make a judgment about the validity of the data. When anomalous data are excluded from the domain of a theory, they obviously do not lead to any theory change.

History of science. Laudan (1977) discusses the example of Brownian motion, which was a phenomenon in search of an explanation beginning in 1828. For nearly a century, it was not clear to which scientific discipline Brownian motion belonged. It was regarded at various times as a biological problem (the motion being caused by small "animalcules"), as a chemical problem, as a problem of electrical conductivity, and as a problem in heat theory. Laudan concludes, "So long as the problem remained unsolved, any theorist could conveniently choose to ignore it simply by saying that it was not a problem which theories in *his* field had to address" (1977, pp. 19-20, italics in original).

Psychology and education. One of the first experiments in psychology to discuss the issue of anomalous data was the work of Karmiloff-Smith and Inhelder (1975; Karmiloff-Smith, 1988). These researchers investigated children attempting to balance blocks on a narrow metal support. Some of the blocks had their weight evenly distributed so that they balanced at their geometric center. Other blocks were uneven, with a mass of lead hidden at one end so that they balanced far off center. By the age of 6 or 7, children had developed a geometric-center hypothesis of balancing; they believed that blocks balance in the middle. But with this hypothesis, they were unable to balance the uneven blocks. When children tried to make the uneven blocks balance in the center, the blocks kept falling off the rail. Instead of changing their geometric-center hypothesis, the children declared that the uneven blocks were impossible to balance, and they did not worry about them further. From our perspective, it appears that the children declared those blocks to be outside the domain of the theory they were developing. In this way, they were able to preserve their theory unaltered.

The commonly observed phenomenon of compartmentalization among science learners can also be viewed as a form of exclusion. Many researchers (e.g., Osborne & Wittrock, 1983; Pines & West, 1986; Roth & Anderson, 1988) have noted that students compartmentalize the science learned in school, keeping it segregated from their theories about how the real world operates. Compartmentalization amounts to excluding classroom science data from everyday theories about how the physical world works.

Holding Anomalous Data in Abeyance

An individual need not come up with an immediate explanation for anomalous data. Individuals who hold a particular theory can place the anomalous data in abeyance, promising to deal with it later. In common with all of the earlier forms of response, placing the data in abeyance leaves the individual's initial theory unchanged. Yet with abeyance, the individual assumes that theory A will someday be articulated so that it can explain the data.

History of science. Thomas Kuhn (1962) has argued that what we have called abeyance is widespread among scientists when they encounter discrepant data: "Even a discrepancy unaccountably larger than that experienced in other applications of the theory need not draw any very profound response. There are always some discrepancies. Even the most stubborn ones usually respond at last to normal practice" (p. 81). A good example of responding to a piece of anomalous data by placing it in abeyance is the treatment of the orbit of Mercury by Newtonian physicists during the late 1800s. It was known for a long period that the details of the orbit were inconsistent with Newtonian mechanics, but no astronomers chose to give up the Newtonian theory. They just assumed that eventually there would be a solution within the Newtonian framework (see T. Kuhn, 1962; Whittaker, 1951).

Psychology and education. Brewer and Chinn (1991, 1992) had undergraduate subjects read a text that offered a nonmathematical explanation of several principles of quantum mechanics. These principles violated certain deeply entrenched beliefs held by most people, such as the belief that physical objects like protons and electrons exist as discrete particles. Then subjects were asked to respond to descriptions of experimental data that supported the quantum mechanics principles but contradicted the subjects' own beliefs. One subject, an undergraduate who had taken five physics courses, held the data in abeyance, confident that physicists would eventually solve the paradoxes of quantum mechanics so that he need not give up his commitment to realism. He wrote, "I do not believe that [quantum mechanics] is true. Though we might not know the answers yet--I do believe that everything exists--whether it is observed or not, and has certain properties either way." In answer to another question, he wrote, "Not sure--I'll tell you in 20 years," indicating his belief that scientists will solve the problem within the realist framework.

Reinterpreting Anomalous Data

An individual can accept anomalous data yet preserve his or her prior theory by reinterpreting the data. The difference between reinterpreting data and rejecting data is that when an individual reinterprets data, that individual accepts the data as something that should be explained by his or her theory. In the case of reinterpretation, supporters of theory A and theory B can agree at some level about the data, but, at a theoretical level, they give different interpretations of the data. As with all of the previous forms of response to anomalous data, reinterpretation does not require a change in the existing theory.

History of science. The decade-long history of scientists' reactions to Alvarez's impact theory of Cretaceous extinctions is rife with reinterpretations. According to Raup (1986), an early reaction to the iridium anomaly was to argue that the iridium might have seeped down into the K-T boundary from layers of limestone above the K-T boundary. This explains the anomalously high concentration of iridium without the need to posit an extraterrestrial source. Note that the data were not rejected: The scientists who advanced the limestone explanation accepted as fact that there was an unusually high concentration of iridium in the K-T boundary layer. But the high concentration of iridium was reinterpreted, and Alvarez's interpretation was not accepted.

Psychology and education. Wisniewski and Medin (1991) provided clear evidence that people sometimes reinterpret evidence to avoid giving up a favored hypothesis. They presented undergraduates with 10 drawings, one at a time. Five of the drawings were allegedly drawn by city children and the other five by farm children. Upon being shown a drawing, subjects guessed whether it had been drawn by a city child or by a farm child; subjects also explained the rule or rules they used to make this guess. Then subjects were given feedback about whether their guesses were correct, and they were invited to modify their rules if they wished. After receiving the feedback, subjects seldom abandoned their rules; instead, they sometimes reinterpreted features in the drawings. For example, one subject originally said that "a drawing was done by a city child because it depicted a television character, and city children watch more television. However, when told that the drawing was done by a farm child, the person reinterpreted the character as one created from a farm child's imagination" (Wisniewski & Medin, 1991, p. 265). Instead of giving up the hypothesis that city children watch more television, the subject chose to reinterpret the evidence.

Piaget (1974/1980, Chapter 6) presented children with a balance scale task and asked them to predict what would happen when one weight was put in each pan. Most young children predicted that one pan would go down and the other up, like a seesaw. After watching the experimenter place one weight in each pan and finding that nothing happened, a 6-year-old hesitated and scrutinized the scale closely. Then the child declared that the pans were in the same place because both weights were light. The child did not reject the data; there was no attempt to deny that the pans were level. But the data were reinterpreted to show that it was only because the weights were too light that the seesaw effect did not occur.

Chinn and Brewer (1992b) have obtained some very extreme examples of reinterpretation. For example, after reading about some anomalous data that were designed to be clearly inconsistent with the meteor impact theory of mass extinctions, one student who supported the theory wrote, "This further proves the meteor impact theory," and he actually increased his rating of how strongly he believed the meteor impact theory.

Making Peripheral Theory Changes

Philosophers of science have argued that anomalous data can never logically compel a scientist to abandon a particular hypothesis because the hypothesis is embedded in a network of beliefs, any one of which might be wrong (Duhem, 1914/1954; Quine, 1951). Lakatos (1970) has distinguished between two types of propositions within a theory: *hard core* propositions and *protective belt* propositions. Hard core propositions cannot be altered without scrapping the entire theory, but protective belt propositions can be altered while preserving the key, central hypotheses. Thus, another response to anomalous data is for the individual to make a relatively minor modification in his or her current theory. An individual who responds in this way clearly accepts the data but is unwilling to give up theory A and accept theory B. This is the first response to anomalous data that we have discussed that involves any change in an individual's initial theory.

A variety of modifications to a theory can fall under the category of peripheral theory change. For example, the individual can add or abandon auxiliary theoretical hypotheses, change beliefs about how experiments in the theoretical domain should be conducted, adjust the definition of a theoretical construct, or alter the domain of the theory. In all of these cases, however, the changes leave the theory's central hypotheses intact.

History of science. The early responses to Galileo's first telescope observations provide a good example of a peripheral theory change. A core assumption of Galileo's opponents was that celestial objects were perfect spheres. After looking through Galileo's telescope, one of Galileo's opponents conceded that he saw mountains on the moon through the telescope. However, he argued that the mountains were embedded in a perfectly transparent crystal sphere (Drake, 1980, p. 48). This peripheral modification of the theory accounted for the anomalous data but allowed the philosopher to retain the core belief that the moon was a perfect sphere.

Psychology and education. There are many psychological and educational studies that provide evidence that nonscientist adults and children frequently respond to anomalous data by making peripheral changes to their theory (e.g., Brewer & Chinn, 1991; Dunbar, 1989; Heller & Finley, 1992; Piaget, 1974/1980; Reiner & Finegold, 1987; Rowell & Dawson, 1983; Schauble, 1990). Here we describe only two representative studies.

Vosniadou and Brewer (1992) have provided evidence for peripheral theory change in children's beliefs about the shape of the earth. They discovered that young children (ages 4-6 years) tend to have a flat earth theory of the shape of the earth. As a result, when young children are told by adults that "the earth is round," they are faced with anomalous information. Some of the children account for this anomalous information by making peripheral changes in their flat earth view. These children interpret the information from the adults to indicate that the earth is a flat disc. Other children adopt a two-earth theory in which there is a flat earth on which people live and a round earth up in space. Both of these belief modifications account for the anomalous information about the earth being round but leave the basic flat earth belief intact.

Lawson and Worsnop (1992) investigated the effects of science instruction on students' beliefs about evolution, and their data suggest that some students who supported creationism made a peripheral change to their creationist theory. More than half of the students in the classes that Lawson and Worsnop studied were creationists. The 3-week instructional unit on evolution included a section on fossil evidence for evolution. Before instruction, only 1% of the students agreed with the statement "Fossils were intentionally put on the Earth to confuse humans." After instruction, however, 7% of the students agreed with the same statement. Our interpretation of this change is that some of the creationist students who were confronted with compelling fossil evidence for evolution adjusted their peripheral beliefs to protect their core belief in special creation. By adding to their theory the peripheral hypothesis that God placed fossils on earth to confuse humans, these students could explain away the anomalous data about fossils.

Subtyping

A very common form of peripheral change is subtyping. As an example, consider the case of an individual who encounters a zebra without stripes. One of the individual's options is to differentiate the category zebra into two subtypes: zebras with stripes and zebras without stripes (cf. Schank et al., 1986).

An example of subtyping from the history of science comes from the work of Wallace, who developed some components of the theory of evolution independently of Darwin. Although, like Darwin, Wallace believed that natural selection and evolution accounted for the bodily structure of humans and all other forms of life, unlike Darwin, he believed that the theory of evolution did not account for the advent of the human intellect. The advent of human intellect could be explained only by invoking the theory of divine intervention (Wallace, 1889). Thus, Wallace differentiated between the human body and the human intellect and developed separate theories to account for the origins of the two subtypes.

In science education, Brown and Clement (1992) found that children subtyped the principles of physics into three different subdomains. They applied one set of principles to the domain of physics in outer space, a second set to the domain of objects falling on earth, and a third set to the domain of objects on the earth.

Changing Theories

The strongest effect that anomalous data can have on an individual is to impel the individual to change to a new theory. By theory change, we mean change in one or more of the theorist's core beliefs. In this form of response to contradictory information, the individual accepts the new data and explains it by changing the core beliefs of theory A or by accepting an alternate theory.

History of science. The history of science suggests that theory change often requires a series of empirical anomalies, which collectively appear to be better explained by an alternate theory (T. Kuhn, 1962; Thagard, 1992). The chemical revolution provides a good example of this type of theory change. After more than a decade of active experimentation, major phlogiston theorists switched one by one to become proponents of Lavoisier's oxygen theory (Musgrave, 1976).

Psychology and education. Most psychological and educational experiments in which some subjects ignore, reject, or reinterpret data or change peripheral beliefs also report that a few subjects do change core beliefs in response to contradictory data. In some studies, major belief change takes more time and shows up only over years as students acquire additional knowledge (e.g., Karmiloff-Smith, 1988;

Vosniadou & Brewer, 1992). In other studies, some theory change in response to anomalous data occurs within one or a few experimental sessions or within several classroom lessons (e.g., Alvermann & Hynd, 1989; Brown & Clement, 1989; Burbules & Linn, 1988; Dunbar & Schunn, 1990; Johsua & Dupin, 1987; Levin, Siegler, Druyan, & Gardosh, 1990; Ranney & Thagard, 1988; Rowell & Dawson, 1983; Zietsman & Hewson, 1986). For example, Rowell and Dawson (1983) found that 3 of 12 subjects who held a weight theory of water displacement changed to a volume theory after observing anomalous data that supported the volume theory. Using the same domain, Burbules and Linn (1988) devised an educational intervention using anomalous data that convinced more than 70% of adolescents to shift from a weight theory of displacement to a volume theory of displacement within a single session.

Summary

When confronted with anomalous data, an individual can make one of seven responses to the data. We think that the evidence that we have provided suggests that these seven categories provide a descriptively adequate account of actual responses to anomalous data. However, we also think that the seven categories can be derived from a logical analysis of the data evaluation and theory-change process.

Responding to anomalous data involves an endeavor to coordinate theory and data (cf. D. Kuhn, 1989; Thagard, 1989, 1992). There are three different decisions an individual must make to coordinate new anomalous data with an existing theory. First, the individual must decide whether the data are believable. This is important because if the data are not believable, then there is no further need to attempt to coordinate data and theory. Second, the individual must decide whether (and, if so, how) the data can be explained. A successful coordination of theory and data requires that the individual be able to explain the data. Third, the individual must determine whether (and, if so, how) the theory needs to be changed to achieve a successful coordination of theory and data. We do not assert that the individual makes these three decisions in any particular order; the decisions may be made in parallel. But all three decisions must be made, either implicitly or explicitly, when anomalous data are encountered.

Thus, attempts to coordinate theory and data involve three fundamental dimensions: (a) whether the individual accepts the data as valid, (b) whether the individual can provide an explanation for why the data are accepted or not accepted, and (c) whether the individual changes his or her prior theory. As Table 1 shows, the seven forms of response to anomalous data differ systematically across these three dimensions.

[Insert Table 1 about here.]

Not all possible permutations across the three dimensions are shown in Table 1. We believe that those permutations not shown are psychologically implausible. For example, it is psychologically implausible that individuals would reject data as invalid yet change their prior theory. It is similarly unlikely that individuals would change their prior theory yet fail to explain the data; the only reason to change a theory in response to anomalous data is to explain the data. Therefore, we believe that the seven categories shown in Table 1 exhaust the psychologically plausible forms of response to anomalous data.

The evidence that we have presented indicates that the seven responses to anomalous data are common to scientists, nonscientist adults, and science students in schools. Thus, when a teacher presents students with anomalous data, they can respond in any one of these seven ways, only one of which is the desired response of changing the current theory. Students may shield their current beliefs by adopting any of six protective responses, from ignoring the data to making only peripheral changes in their current theory. In the remainder of this report, we will refer to these six responses as *theory-preserving responses*.

If teachers are to use anomalous data to effect theory change, they must understand the factors that interact to determine how students respond to such data. What causes a student to reject data instead of changing the current theory? Why does a student make only peripheral changes to a preinstructional theory in one instance but change a preinstructional theory in another instance? What are the conditions that make it less likely that a student will make theory-preserving responses and more likely that the student will change theories?

In the next section, we will explore answers to these questions. We will examine research directed at understanding the conditions that lead to different responses to anomalous data.

Conditions that Lead to Different Responses to Anomalous Data

In this section, we discuss the factors that influence how a person responds to anomalous data. We do not attempt to be exhaustive in our enumeration of these factors. Instead, we confine our analysis to factors for which we believe there is good evidence. Once again, we rely on evidence from the history of science, evidence from psychology, and evidence from education.

We propose that there are four key components that interact to determine how people respond to anomalous data: (a) an individual's prior knowledge, (b) a possible alternative theory, (c) the anomalous data, and (d) the processing strategies that guide the evaluation of the anomalous data. These four components can be analyzed into more specific characteristics that influence how an individual responds to anomalous data. These characteristics are displayed in Table 2. In this section, we discuss each component and each characteristic, and we explain how and why they influence the response to anomalous data.

[Insert Table 2 about here.]

Characteristics of Prior Knowledge

We postulate that there are four characteristics of prior beliefs that are especially important in influencing how an individual responds to anomalous information: (1) the entrenchment of the individual's current theory, (2) the individual's ontological beliefs, (3) the individual's epistemological commitments, and (4) the individual's background knowledge.

Characteristic 1. Entrenchment of the Prior Theory

An entrenched theory is a theory that contains one or more deeply entrenched beliefs. An entrenched belief is a belief that is deeply embedded in a network of other beliefs (see Brewer & Chinn, 1991; P. Hewson, 1981; Posner et al., 1982; Vosniadou & Brewer, 1992). More specifically, a deeply entrenched belief is one that (a) has a great deal of evidentiary support and (b) participates in a broad range of explanations in various domains. In addition, a belief may be entrenched because it satisfies strong personal or social goals. Thus, among small children, the belief that the earth is flat is entrenched because it is strongly supported by daily observations. Among scientists, the principle of the conservation of mass and energy is entrenched because it is used to support successful explanations in many domains, from particle physics to astronomy. And among smokers, the belief that smoking will not harm one's health may be entrenched because believing otherwise is incompatible with the goal of smoking.

The more entrenched a belief, the harder it should be to persuade an individual to change the belief. An individual who holds a deeply entrenched belief is unlikely to change the belief. Confronted with a piece of anomalous data, the individual who holds a deeply entrenched theory will seek to ignore it, reject it, exclude it, hold it in abeyance, or reinterpret it. If hard pressed by anomalous data, the individual may make peripheral changes to the theory. Only if confronted with very convincing anomalous data will the individual abandon an entrenched belief.

In empirical work, it is necessary to ensure that the assessment of entrenchment is independent of the assessment of theory change. This avoids the circularity of saying that entrenched beliefs are hard to change, and one knows that the beliefs are entrenched because they are hard to change. A number of studies that meet this criterion provide support for the position that individuals are less likely to give up entrenched beliefs than nonentrenched beliefs (Chinn & Brewer, 1992a; Hewson, 1982; Klahr, Dunbar, & Fay, 1990; Kunda, 1987; Swann, Pelham, & Chidester, 1988; Wu & Shaffer, 1987; also see Kunda, 1990; Reinard, 1988). Although most of these studies do not use the term *entrenched*, each supports the idea that beliefs that have strong evidentiary support, participate in a broad range of explanations, or satisfy strong personal or social goals are especially hard to change.

Chinn and Brewer (1992a) attempted to manipulate entrenchment, and then assessed the effects of entrenchment on theory change. Undergraduates were presented with a text describing the meteor impact theory of dinosaur extinctions. Subjects in the entrenched condition received numerous pieces of evidence supporting the theory, including the evidence that the crater had been found. Subjects in the nonentrenched condition were given only one piece of evidence in support of the theory. As predicted, subjects in the entrenched condition were less likely to abandon the meteor impact theory than were subjects in the nonentrenched condition.

The studies listed earlier make it clear that entrenched beliefs are hard to change. Only a few studies, however, have explored the effects of entrenchment on how people appraise anomalous data. Brewer and Chinn (1991) presented undergraduates with texts that contradicted entrenched beliefs in the domains of special relativity and quantum mechanics. They found that although many subjects *understood* the new theories quite well, as shown by their ability to answer transfer questions, they did not *believe* the new theories. And when confronted with anomalous data, the subjects' responses fit into the categories of rejection, exclusion, abeyance, reinterpretation, and peripheral change. No subjects gave evidence of abandoning their entrenched beliefs.

Sherman and Kunda (reported in Kunda, 1990) had subjects read a text describing a study reporting that heavy caffeine consumers were at risk of developing a serious disease. Some subjects were high-caffeine consumers; others were low-caffeine consumers. Subjects who were high-caffeine consumers were less likely to be persuaded by the study, and they correspondingly rated various methodological aspects of the study as less sound than did low-caffeine consumers. Thus, high-caffeine consumers, who presumably were more committed to the belief that caffeine is not harmful than were low-caffeine consumers, attempted to discount the anomalous data (see also Pyszczynski, Greenberg, & Holt, 1985).

The Sherman and Kunda study illustrates another point about entrenched beliefs. Sometimes a belief is entrenched for reasons of personal self-image or for social expediency. Scientists themselves believe that a scientist's commitment to a theory is influenced by such factors as personal rivalry, emotional involvement, protecting one's reputation, and fear of being discredited with agencies that evaluate grant proposals (Mulkay & Gilbert, 1982). It may require very convincing anomalous data to overcome these social sources of entrenchment.

An interesting question about entrenched theories is whether well-developed theories are necessarily entrenched. Crocker, Fiske, and Taylor (1984) have argued that well-developed schemas should be more resistant to change than the poorly developed schemas of novices (also see Chaiken & Yates, 1985; Tesser & Leone, 1977). Against this, Strike and Posner (1985) note that it is perfectly possible to have a well-developed schema of Marxist economic theory without believing it. And Schauble, Glaser, Raghavan, and Reiner (1991) found that subjects with better developed models of the behavior of electrical circuits were actually more likely to change their beliefs in the face of anomalous data than were subjects with poorly developed models. One reason appeared to be that subjects with poorly developed models were unable to make the conceptual distinctions necessary to interpret the anomalous data meaningfully. "Knowledge that is unconnected, isolated, and local can fail to provide any sustaining inference power that would serve to guide and evaluate new interpretations of data" (p. 227). It appears, then, that well-developed schemas are not necessarily entrenched. The key is whether the schema is also embedded in evidentiary support and is used to support a wide range of other theories and observations that the person believes.

Characteristic 2. Ontological Beliefs

There is one class of theoretical beliefs that is so deeply entrenched that it deserves special mention: the class of ontological beliefs (i.e., beliefs about the fundamental categories and properties of the world; see Keil, 1979). Because these beliefs are used to support ideas across many domains or subdomains and because the beliefs are remote from experience, they are very hard to change (see Chi, 1992). Examples of mistaken ontological beliefs that have been found to resist change are beliefs that objects like electrons and photons move along a single discrete path (Brewer & Chinn, 1991), that time flows at a constant rate regardless of relative motion (Brewer & Chinn, 1991; P. Hewson, 1982), that heat is a substance (Wiser, 1988), and that force is something internal to a moving object (McCloskey, 1983). Chi (1992) has argued that many misconceptions in the physical sciences are caused by faulty ontological underpinnings, namely, that concepts like heat, light, force, and current are believed by children to be a material substance. These faulty ontological assumptions not only lead students to reject accepted scientific ideas but also make it difficult for the students even to comprehend the accepted scientific ideas. Thus, they lead students to make theory-preserving responses to anomalous data.

Characteristic 3. Epistemological Commitments

Epistemological commitments in science are beliefs about what scientific knowledge is and what counts as a good scientific theory (e.g., Posner et al., 1982; Samarapungavan, 1992; Toulmin, 1972). These beliefs, too, are relatively immune to change because they are used to support ideas in many different subdomains.

There is evidence that even the youngest elementary school students are guided by a sound "common sense" epistemology (see Conant, 1951) when they choose between theories. Samarapungavan (1992) found that first graders prefer theories that are internally consistent, that are consistent with empirical evidence, and that cover a broad range of evidence instead of a narrow range. She also found that a substantial majority of fifth graders additionally preferred explanations that are not ad hoc to those that are ad hoc. Samarapungavan's results strongly suggest that children come to school already equipped with some of the criteria for judging among scientific theories, criteria that have been proposed by such philosophers of science as T. Kuhn (1977) and Laudan (1977) as rational criteria for making choices among scientific theories.

However, although children possess an adequate commonsense epistemology, they undoubtedly lack more sophisticated epistemological commitments based on the scientific cultural tradition that began to develop during the Renaissance (Brewer & Samarapungavan, 1991); these include commitments to such ideas as testing hypotheses experimentally and using rigorous controls. In addition, it appears that children (and even some adults) do not make the same sharp distinction between theories and evidence that scientists do (Carey, Evans, Honda, Jay, & Unger, 1989; D. Kuhn, 1989; D. Kuhn, Amsel, & O'Loughlin, 1988).

Moreover, many school-aged children possess epistemological beliefs about the scientific enterprise that are likely to impede rational theory change. For example, many students appear to believe that learning science amounts to memorizing facts and that science does not apply to the everyday world (Songer & Linn, 1991). Carey et al. (1989) found that a majority of seventh graders believed that scientific knowledge is a faithful copy of nature and that scientific inquiry is a Baconian process of observing facts rather than a process of constructing theories to account for empirical observations.

What epistemological beliefs might facilitate theory change in response to anomalous data, as opposed to theory-preserving responses to the data? It certainly seems probable that helping students achieve explicit metaconceptual knowledge of how theories relate to evidence would promote a more rational theory evaluation process. Reif and Larkin (1991) argue that students must understand that science demands a much more rigorous consistency than does the more mundane theorizing in everyday life. Nickerson (1991) advocates a sense of "active fair-mindedness," in which people actively consider evidence on both sides of an issue, even giving special consideration to evidence contrary to their current positions. Easley (1990) argues that students must understand that science is more a process of discovery than a body of static knowledge and that there is nothing wrong with changing a theory. Moreover, students should understand that science is often controversial, involving a continual process of debate about evolving alternative theories. Although it is plausible to assume that epistemological beliefs such as those presented above might make theory change more likely, we know of no studies that have investigated the effects of epistemological beliefs on how individuals respond to anomalous information.

Characteristic 4. Background Knowledge

An individual's background knowledge is an extremely potent factor in determining how the individual responds to anomalous data. We are using the term *background knowledge* in the same way as Shrager and Langley (1990). Background knowledge is scientific knowledge that an individual assumes to be valid but that is not specifically part of the theory under evaluation. For example, astronomers who are testing theories about the origin of the universe simply assume that their mathematical knowledge, their knowledge about chemical spectra, and their knowledge about how radiotelescopes work are true; these bodies of knowledge are not regarded as part of the theories to be evaluated.

Depending on its contents, an individual's background knowledge can have very different effects on how the individual responds to anomalous data. On one hand, background knowledge can lead an individual to reject or reinterpret anomalous data. On the other hand, background knowledge can lead the individual to accept the anomalous data and to make either peripheral or core changes to the current theory.

To illustrate how background knowledge can lead an individual to reinterpret anomalous data, recall the response of some scientists to the meteor impact theory of mass extinction at the end of the Cretaceous period. The scientists reinterpreted the iridium anomaly by saying that iridium had seeped down into the K-T boundary from the layers of limestone above the K-T boundary. The scientists could respond in this way only because they had access to a great deal of relevant background knowledge: There are limestone layers above the K-T boundary, water seeps through limestone, chemicals contained in limestone can seep down together with the water, these chemicals are deposited at the first layer of harder rock below the limestone, and the K-T boundary layer is harder than the limestone. If any of these pieces of background knowledge had been missing, the scientists would have been unable to reinterpret the iridium anomaly in this way.

A study by Lord, Ross, and Lepper (1979) provides indirect experimental support for the idea that accessible background knowledge can lead to the rejection of anomalous data. Half of the undergraduate subjects in this study were in favor of capital punishment and believed that relevant research supported its deterrent effect; the other half were opposed and believed that the relevant research showed that it did not have a deterrent effect. Each subject read a brief report of a study that contradicted his or her position on the relationship between capital punishment and deterrence. Afterward, subjects rated their belief in the deterrent effect of capital punishment. Results showed that subjects were swayed by the data they had read and became less sure of their positions. Then subjects read a critique of the study they had just read. The criticisms concerned problems with the study's methodology. Reading these criticisms completely reversed the effects of the contradictory data. Subjects then rejected the study they had read on methodological grounds, and they actually became more convinced of their original position than they had been prior to the study!

From our perspective, it appears that when the subjects in this study first read the anomalous data, they were unable to spontaneously access information that would allow them to reject the study on methodological grounds (cf. Kunda, 1990). Hence, the anomalous data weakened their original opinion. But the criticisms that they subsequently read supplied them with the "background information" that they needed to reject the anomalous data. We conjecture that if the subjects had been able to access methodological criticisms from their own background knowledge, they would have rejected the data from the start.

In a study described earlier, Chinn and Brewer (1992a) found more direct evidence that background knowledge can lead people to reject or reinterpret anomalous data. Undergraduates who had learned about the meteor impact theory of dinosaur extinctions were then presented with data that contradicted the meteor impact theory. The subjects relied heavily on their background knowledge as they evaluated the anomalous data. For example, one subject was given data from a laboratory simulation purporting to demonstrate that a meteor impact would kill all life on earth because it would throw up so much dust that all sunlight would be completely blocked for 18 months. This subject used background knowledge to reject the data: "The earth is much too big and different to be correctly represented by some small rock in a laboratory. Things like atmosphere, spin, gravity, etc. play a part as well" (p. 169). Another subject used background knowledge not to reject the idea that the earth would be dark for 18 months but to reinterpret the evidence to show that all life would not be killed: "*Some* things could survive with no light, for example, anaerobic respirators" (p. 169).

Our position, then, is that subjects will reject or reinterpret anomalous data if they can access relevant background knowledge. This means that issues of accessing knowledge that have been studied by such researchers as Gick and Holyoak (1983), Ross (1987), and Catrambone and Holyoak (1989) are crucial to understanding how people respond to anomalous data.

An ironic consequence of our position is that a lack of background knowledge can actually facilitate theory change! Thus, in the Lord et al. (1979) study, subjects were more convinced by anomalous data before they encountered information that could be used to reject it. If this view is correct, then theory change should be relatively easy when subjects have little background knowledge that they can use to evaluate evidence. However, if an individual possesses *too* little background knowledge, he or she will not even be able to understand that the anomalous data are anomalous (cf. Lijnse, 1990; Longino, 1990). Suppose that someone who does not know that meteors contain iridium is told, "The best evidence for the impact theory of Cretaceous extinctions is the unusually high concentration of iridium in the K-T boundary." The person is unlikely to understand why the iridium is relevant. This could lead the person to ignore or exclude the evidence.

So far we have portrayed background knowledge as a villain in the theory-change process because such knowledge often leads an individual to reject or reinterpret anomalous data. But background knowledge can also compel an individual to accept anomalous data, even when the data contradict an entrenched theory. A good example is the case of the Piltdown skull, which was "discovered" in 1912 in an English gravel pit. The skull appeared to belong to an early hominid that had lived in what is now the British

Isles, but 40 years later it was determined to be a hoax. Soon after the original discovery, several scientists argued that the Piltdown skull was not an early hominid but merely a chance mixture of the skull of a human and the jaw of an ape. This reinterpretation was countered by the hoaxster, who planted pieces of another fraudulent skull at another site in England. When these were found, the scientists abandoned their reinterpretation. Their background knowledge told them that the odds of finding the same combination of human and ape bones in two separate sites were too small to be credible; hence, they concluded that the Piltdown skull had to be genuine (Weiner, 1955).

Many such examples can be provided from the history of science, and there is also evidence from social psychology that people's background knowledge can constrain them to accept anomalous data. In a wide-ranging review of the social psychological literature, Kunda (1990) has concluded that "people attempt to be rational: They will believe undesirable evidence if they cannot refute it . . . ." (p. 490). And "people are not at liberty to believe anything they like; they are constrained by their prior beliefs about the acceptability of various procedures" (p. 490). Thus, background knowledge can also facilitate acceptance of a well-done study.

In science education, it seems reasonable to assume that children who have internalized some of the accepted canons for evaluating scientific experiments will be willing to accept anomalous data when the data conform to those canons. Many children, however, have not learned these standards. A large body of developmental research indicates that children (and even many adults) are deficient in their understanding of such methodological matters as controlled experimentation and the interpretation of covariation information (e.g., Gil & Carrascosa, 1985; Kuhn, 1989; Kuhn et al., 1988; Schauble, 1990; Shaklee & Elek, 1988; Shaklee & Goldston, 1989). As a result, when children are presented with covariation information that contradicts a favored theory, they are not constrained to accept the information, and they find it easy to retain their favored theory. In our view, the children are hampered in their informed response to anomalous data by a lack of relevant background knowledge related to the evaluation of scientific studies.

Characteristics of the New Theory

In this section, we discuss two characteristics of the new theory that influence the individual's response to anomalous data: (1) the availability of a plausible alternative theory and (2) the quality of the alternative theory, which includes the accuracy, scope, consistency, and simplicity of the theory. In addition, we discuss a third characteristic of the new theory that may not be strictly necessary for theory change but that is certainly necessary for informed theory change: the intelligibility of the alternative theory.

Characteristic 1. Availability of a Plausible Alternative Theory

T. Kuhn (1962) has argued that scientists will not give up a theory unless there is a plausible alternative theory available, and Posner et al. (1982) have made essentially the same argument about science learners. This idea has strong support both in the history of science and in the psychological literature.

The history of science shows that scientists frequently choose to make theory-preserving responses to anomalous data when the data are not accompanied by a plausible theory. For most scientists, the essential ingredient in a plausible theory is a plausible physical *mechanism* (see Harré, 1988). The case of continental drift provides an example. As we noted earlier, Wegener conceived of the theory of continental drift in order to account for the congruence in the shorelines of Africa and South America. Wegener's theory explained several other anomalous facts besides the shape of the Atlantic coastlines. For example, it explained why many species of fossils were found on both sides of the Atlantic. But Wegener could find no plausible physical mechanism that could move whole continents. He suggested that the gravitational forces of the sun and moon and tangential movements toward the equator caused by the earth's rotation could combine to cause continents to move, but critics pointed out that these forces were much too weak to be a plausible mechanism (Thagard & Nowak, 1990). It was not until the development of plate tectonics provided a viable mechanism for the movement of continents that the hypothesis of continental drift became respectable (Stewart, 1990). Discussing a similar historical case, Gould (1980) notes, "Events that 'cannot happen' according to received wisdom rarely gain respectability by a simple accumulation of evidence for their occurrence; they require a mechanism to explain how they *can* happen" (p. 167, italics in original).

Like scientists, children respond to data in theory-preserving ways when no plausible mechanism is available to account for the anomalous data. Deanna Kuhn (1989) has presented evidence that children refuse to acknowledge anomalous covariation data until they can generate a theory to account for the data. For example, a child might believe that the type of cola (diet or regular) that a person drinks is unrelated to colds. Then the child might be presented with covariation evidence that shows that people who drink regular cola are more likely to get colds. As the anomalous information is presented little by little, subjects at first resist the implications of the covariation evidence, and they do not acknowledge the evidence until they have thought of a new theory explaining why regular cola causes colds. Kuhn argues that such data show that children are very different from scientists, but it appears to us that the children are behaving very much like scientists in an essential respect. Although scientists are undoubtedly better able than children to acknowledge that anomalous covariation evidence exists even though they do not believe it, scientists and children are similar in their refusal to accept anomalous evidence as valid until they can generate an alternative mechanism.

Further evidence for the importance of a plausible mechanism comes from the study by Johsua and Dupin (1987) that we discussed earlier. As we noted, children in that study believed that current "wore out" as it traveled around a circuit. The children strongly resisted the idea that current is constant throughout a simple circuit, and even large amounts of evidence did not change their minds. The reason for their stubbornness was that they needed a mechanism that would explain why batteries wear out. They believed that the only way to account for the battery wearing out was to assume that the current returning to the battery was slightly less than the current leaving the battery. In this way, the battery would gradually lose its ability to generate current. The children did not change their minds until the teacher used an analogy to explain how the battery could lose energy while the current remained constant around the circuit. This analogy convinced the students that the equal-current hypothesis was supported by a plausible mechanism, and only then did they change their theory.

In the absence of a plausible alternative theory, people may cling to a theory even though they know it is inadequate. In a rule discovery task, Klahr and Dunbar (1988) found that subjects who had no alternative hypotheses readily available were less likely to abandon a hypothesis that had been disconfirmed by anomalous data than were subjects who had a readily available alternative. Apparently, a bad theory was better than no theory at all (also see Einhorn & Hogarth, 1986).

Characteristic 2. Quality of the Alternative Theory

T. Kuhn (1977) has argued that a good scientific theory has at least five characteristics. First, a good theory is *accurate*, which means that it is consistent with known data in its domain. Second, a good theory explains a broad *scope* of data. Third, it is *consistent*, in two ways. It is internally consistent, and it is consistent with other accepted scientific theories. Fourth, it is *simple*, which means that it brings order to otherwise isolated phenomena. And, fifth, it is *fruitful*, which means that the theory should generate new research results. We use the term *quality* to refer to the combination of these five characteristics. Rational choice between competing theories requires scientists to weigh the theories across these characteristics. This process " depends on a mixture of objective and subjective factors . . . ." (T. Kuhn, 1977, p. 325).

Evidence from the history of science bears out the importance of these five characteristics in theory change among scientists. Thagard (1989, 1992) has captured some of the effects of these five characteristics (together with a few other characteristics) in a connectionist model of scientific revolutions. He uses the term *explanatory coherence* to refer to a property of theories that is much like what we have called the quality of a theory. Thagard (1992) has modeled historical scientific revolutions in the domains of chemistry, evolution, plate tectonics, astronomy, Newtonian physics, and relativistic physics. He (Thagard, 1992) concludes that "for most revolutions, the explanatory breadth of the new theory--how much it explains--is the largest contributor to explanatory coherence" (p. 248). He adds that simplicity usually plays a role, and accuracy, internal consistency, and consistency with other knowledge often play a role, as well.

How does the quality of a theory affect the response to anomalous data among nonscientists and science students? It seems reasonable to assume that if an alternative theory ranks highly on these five characteristics, individuals will be more likely to change theories and less likely to make theory-preserving responses to anomalous data. There is at least some psychological and educational evidence for three of the characteristics: accuracy, scope, and consistency. There is as yet no firm evidence for simplicity or fruitfulness.

Accuracy. There is strong evidence that the relative accuracy of theories is important for science learners. Indeed, the instructional use of anomalous data in the classroom relies primarily on the idea of accuracy: learners will come to reject their own theory because it cannot accurately account for the anomalous data, and they will accept the alternative theory because it does account for the anomalous data. A number of studies have found that anomalous data produce this effect with at least some students (e.g., Burbules & Linn, 1988; Inagaki & Hatano, 1977; Johsua & Dupin, 1987; Nussbaum & Novick, 1982; Rowell & Dawson, 1983).

Scope. Recently researchers have begun to address the combined effects of accuracy and scope. In the Chinn and Brewer (1992a) experiment described earlier, it appeared that subjects juggled accuracy and scope as they chose between theories. After reading about various pieces of evidence that supported either the meteor impact theory or the volcano theory of Cretaceous extinctions, subjects rated their belief in the two alternative theories. Subjects in the entrenched condition had read 11 pieces of data, including the iridium anomaly and evidence about the discovery of a crater that was just the right age and size to have caused the extinctions. The meteor impact theory was able to explain 9 of the 11 pieces of data but was incompatible with the other 2 pieces. The volcano theory could explain 3 of the 11 pieces of data. Subjects strongly preferred the meteor impact theory, in part because it explained a broader scope of data. By contrast, subjects in the nonentrenched condition had read only 3 pieces of data. The meteor impact theory could explain only 1 piece of data; the volcano theory was consistent with all three. As expected, these subjects preferred the volcano theory. Thus, subjects in each condition preferred the theory that accurately accounted for the broadest scope of data.

Schank and Ranney (1991) have similarly found that subjects prefer theories that cover a broader scope of empirical data. They used simple fictional scientific disputes to minimize the impact of prior knowledge. Under these conditions, they found that the scope of evidence that alternative theories could explain played an important role in choices about theory. When one theory could explain three of four pieces of evidence and the other could explain only two of the four, subjects chose the theory with broader empirical scope.

Consistency. There is some evidence that logical consistency affects students' theorizing. Using a task in which children were asked to choose between two different theories that explained a body of data, Samarapungavan (1992) found that even first graders strongly preferred theories that were logically consistent to theories that contained logical inconsistencies. Similarly, Levin et al. (1990) reported that when researchers pointed out to children the logical inconsistencies in their theories, 45% of the children altered their theory to make it logically consistent. Thus, children are frequently sensitive to logical inconsistencies in theories.

Characteristic 3. The Intelligibility of the New Theory

Posner et al. (1982) have argued that an alternative theory will not be accepted unless it is intelligible. This is obviously true at some level. A 5-year-old could not accept quantum mechanics because quantum mechanics would be utterly incomprehensible to someone with the knowledge possessed by 5-year-olds. And it is equally obvious that rational, informed theory change requires that the student understand the new theory. Without a good understanding of the new theory, the student may not even be able to understand the significance of the anomalous data that support the new theory.

It may not be strictly true, however, that a new theory must be understood before students will adopt it. Linn and Songer (1991) found that many students studying thermodynamics adopted a facile conception of heat and temperature that they did not fully understand, as shown by their inability to apply the conception. Linn and Songer argued that the students were acting as "cognitive economists," saving on cognitive effort as often as possible. Many studies in social psychology similarly show that people will sometimes adopt beliefs in a manner that expends the least cognitive effort (see Cooper & Croyle, 1984; Tesser & Shaffer, 1990). It seems, then, that people sometimes adopt a new theory without fully comprehending it. Although understanding scientific theories is crucial for meeting the goals of science education, understanding may not be an indispensable prerequisite for belief change.

Characteristics of the Anomalous Data

We propose that there are three characteristics of anomalous data that influence the response to such data: (1) the credibility of the data, (2) the ambiguity of the data, and (3) the existence of multiple data to rule out prior theory-preserving responses.

Characteristic 1. Credibility

To avoid rejection, anomalous data must pass the test of credibility. Data that are not credible will be rejected. Data that are credible may produce the responses of exclusion, abeyance, reinterpretation, peripheral theory change, or theory change, but not rejection. Thus, to have any chance at promoting theory change, the data must be credible. There are numerous ways to increase the credibility of anomalous data.

The first way is to increase the credibility of the source of the data. Social psychologists have found that more credible communicators produce more belief change, and credibility is enhanced when the communicator is unbiased and when the communicator is an expert (Hovland, Janis, & Kelley, 1953; Maddux & Rogers, 1980; Reinard, 1988). If we extend these ideas to science, we would expect the scientist's expertise, or at least his or her reputation for expertise, to affect the reception of his or her experimental results. The history of science suggests that this is indeed the case. For example, one physicist wrote of his reaction to Röntgen's report of the discovery of X rays, "I could not help thinking that I was reading a fairy tale, though the name of the author and his sound proofs soon relieved me of any such delusion" (Glasser, 1934, p. 29). Lord Kelvin was skeptical of the famous Michelson-Morley experiment because he did not trust Michelson's "experimental skill" (Lakatos, 1970, p. 161).

With science students evaluating contradictory scientific ideas, it may be necessary to consider separately the credibility of the teacher and the credibility of the scientists whose achievements the teacher relates. Shrigley (1976) reports evidence that preservice teachers are sensitive to the credibility of teacher trainers in the field of science, and Koballa and Shrigley (1983) argue that a science educator's credibility in the eyes of students may be important in influencing whether students believe what the teacher says.

The second way to enhance credibility is to follow accepted methods of data collection and analysis (cf. Mahoney, 1976). A clinical trial of a new drug would be unlikely to convince the medical community if it had no control condition or if it did not use a double-blind procedure. Following accepted procedures is no guarantee of acceptance, but failure to do so probably guarantees rejection.

A third way to enhance credibility is through replication. According to Close (1991), when Pons and Fleischmann reported in 1989 that they had achieved cold fusion, there was an immediate worldwide attempt to replicate the findings. The overwhelming majority failed to replicate. Moreover, "the research groups for cold fusion tend to be small and tend to be relatively 'amateur' compared with the full-time, large-scale teams of laboratory scientists who have, almost universally, seen nothing" (p. 50). (This example also shows the effects of credibility and accepted methods of data collection.) By contrast, Röntgen's discovery of X rays was quickly embraced by the scientific community as laboratories throughout the world replicated his findings; within months, there were even public demonstrations of X rays at such sites as Bloomingdale's department store in New York City (Nitske, 1971).

A fourth possible way to enhance credibility is to allow people to observe the experimental results directly. Thus, classroom demonstrations and laboratories might be more likely to produce theory change than simply having students read about an experimental result. Some instructional studies have provided support for this notion. Brown and Clement (1992) reported that increased use of hands-on experiences appeared to facilitate conceptual change in mechanics. Alvermann, Hynd, and Qian (1990) found that a demonstration coupled with reading a text was superior to merely reading the text in producing conceptual change in the domain of projectile motion.

Finally, there is one form of data that is perfectly credible, data that the individual already believes. Dreyfus et al., (1990) provide an example (also see Collins, 1977). In a discussion, students had asserted that a cell membrane operates by selectively identifying the "things" that the cell needs, letting them into the cell, and excluding things that the cell does not need. The interviewer then pointed out that cells can be poisoned, which should not happen if cells let in only substances that the cell needs. These data prompted the students to revise their theories. Thus, the interviewer brought to the students' attention anomalous data that the students already knew about but that they had not connected with their theory of membrane operation.

Characteristic 2. Ambiguity of the Data

Even if the anomalous data are completely credible, they may be vulnerable to reinterpretation. Although it is undoubtedly true that *any* data can be reinterpreted, it also seems clear that some data are more easily reinterpretable than others. In other words, some data are relatively unambiguous with respect to two competing theories; other data are relatively ambiguous. Unambiguous data should increase the likelihood of theory change; ambiguous data should make reinterpretation very easy.

Some philosophers and historians of science have doubted that data can be completely unambiguous with respect to two competing theories because they believe that data are theory laden and thus some theories are incommensurable (e.g., Hanson, 1958; T. Kuhn, 1962). According to this view, rival theories frequently possess qualitatively different concepts and use different vocabularies to report what is observed. Because it is impossible for supporters of competing theories to find a common, neutral vocabulary to characterize observed data, the rival theorists cannot agree on what they are observing. As a result, crucial data are frequently ambiguous with respect to the competing theories.

More recent historical research has called this view into question. It now appears that in most actual scientific disputes, supporters of competing theories are able to find a common, neutral vocabulary for discussing at least some data. In other words, rival theorists can frequently agree that their respective theories make different predictions for some subset of experiments or observations (Suppe, 1977; also see the postscript to T. Kuhn, 1970). As an example, during the historical debate over the heliocentric and geocentric theories of the cosmos, many heliocentric theorists and geocentric theorists did agree that there was one observation for which their theories unambiguously made different predictions. Both sides agreed that if it is true that the earth travels many millions of miles as it circles the sun, there should be a shift in the position of the stars every 6 months as the earth moves from one side of the sun to the other. On the other hand, if the earth is stationary, there should be no shift in the position of the stars (see Toulmin & Goodfield, 1961). When early astronomical observations repeatedly failed to show any shift in the stars, the heliocentric theorists were placed in a very uncomfortable position.

What are the effects of ambiguous and unambiguous data on data evaluation? In the history of science, ambiguous anomalous data are frequently reinterpreted within the current theory. For example, Brewer and Lambert (1992) argue that degraded, ambiguous perceptual data are often interpreted through theory-laden perception processes. They describe the historical case of early observations of Saturn. Early telescopes presented a relatively ambiguous image of Saturn. Most observers thought that Saturn's features were due to satellites, and that is what they reported seeing when they observed Saturn. However, other astronomers believed that Saturn had a ring, and they reported seeing a ring when they observed Saturn (Helden, 1974). But it seems to us that no one who views one of the unambiguous photographs taken by one of the Voyager spacecraft could possibly doubt that Saturn is encircled by a ring. Ambiguous data thus encourage reinterpretations; unambiguous data preclude such reinterpretations.

In the history of science, unambiguous data against a theory sometimes nudge scientists toward eventual theory change (cf. Badash, 1966; Musgrave, 1976), but unambiguous data often produce abeyance or peripheral change instead. In the case of the debate between heliocentrists and geocentrists, the failure to find a shift in the position of the constellations did not force prominent heliocentrists to give up their theory (see Toulmin & Goodfield, 1961). Copernicus responded to the data by making a peripheral theory change; to explain why no shift was found, he introduced the assumption that the stars were very, very far from the earth. Although this later proved to be correct, it appeared at the time to be a very ad hoc assumption. Kepler apparently placed the anomaly in abeyance and continued to try (futilely) to detect a constellation shift through more careful observations (Toulmin & Goodfield, 1961).

There is psychological evidence that ambiguous information allows a person to reinterpret the information to be consistent with his or her current framework. Anderson, Reynolds, Schallert, and Goetz (1977) presented college students with texts that could be interpreted either as a prisoner planning an escape from prison or as a wrestler planning an escape from his opponent's hold. Each sentence was ambiguous with respect to the two interpretations (e.g., "The lock that held him was strong but he thought he could break it"). College students who were wrestlers tended to interpret these ambiguous passages as referring to a wrestler; music students preferred the more natural prisoner interpretation. It seems clear, however, that the students could sustain their preferred interpretations only because the sentences were ambiguous. It seems certain that less ambiguous sentences, such as "The steel alloy lock that held him in the jail cell was strong but he thought he could break it," would preclude the wrestler interpretation and unambiguously lead a person to choose the prisoner framework.

There is also psychological evidence that unambiguous data promote theory change. In social psychology, Jussim (1991) makes a convincing case that reliable, unambiguous social data are not interpreted with bias and that people adjust their theories to encompass such data. And in cognitive psychology, Mynatt, Doherty, and Tweney (1977) found that although most subjects who obtained ambiguous disconfirming data on a rule discovery task retained their incorrect hypotheses, 91% of the subjects who obtained unambiguous disconfirming data changed to a correct or partly correct hypothesis.

Research by Stavy (1987, 1991) suggests that unambiguous data are more effective than ambiguous data in promoting theory change among science students. The domain was the conservation of mass when liquids are heated. When the experimenter demonstrated the principle of conservation of mass by heating liquid acetone, which is clear and produces a clear gas, students resisted the conclusion that weight was conserved. But when the experimenter instead heated liquid iodine, which is blue and produces a clearly visible blue gas, students were much more likely to agree that weight was conserved. Moreover, once students accepted that weight was conserved in the case of iodine, many of them also accepted that weight was conserved in the case of acetone. Thus, by choosing anomalous data that unambiguously showed iodine gas remaining in the test tube, the experimenter successfully convinced many students to change their theory.

Characteristic 3. Multiple Data to Systematically Rule Out Discrediting Responses

It is hard for a single piece of data to be immune to all possible methodological criticisms and to all possible reinterpretations. In order to meet these types of objections, scientists will frequently provide a set of data, each individual study designed to counter particular objections to earlier data.

In scientific practice, the usual way to rule out specific methodological criticisms and specific reinterpretations is to conduct multiple studies. This can be done in two ways. The first way is to try to anticipate in advance what the objections will be and to conduct multiple experiments to rule out these objections. Röntgen used this approach in his initial research on X rays. After Röntgen first discovered X rays, he spent the next 8 weeks in secrecy, conducting numerous experiments with the strange new rays in order to rule out all the possible grounds he could think of for rejecting or reinterpreting his data (Glasser, 1934, Chapters 1 and 2).

The second way to rule out rejections and reinterpretations is to find out post hoc what the objections are and then to conduct further studies to counter these objections. Scientists often keep gathering new data for years to try to rule out rejections and reinterpretations that have been made of earlier anomalous data (see, e.g., Musgrave, 1976).

The point is that one crucial way to undermine a counterargument that has been made against anomalous data is to gather data that are designed to target the specific counterargument. In other words, the scientist attempts to find out precisely what beliefs are causing the resistance to the anomalous data and then goes specifically after those beliefs.

In science education, like science itself, there are two ways to rebut students' theory-preserving responses. The first way is, again, to anticipate in advance what the grounds for rejection and reinterpretation will be and to prepare lines of data in advance to undermine those objections. Brown and Clement (1992) used this approach when they implemented classroom interventions designed to teach Newtonian physics in two successive years. They report that the second year's intervention was much more successful than the first, and they believed that part of the reason was that in the second year, they had a much more detailed understanding of students' alternative conceptions. They used their more detailed understanding to plan experiments to counter specific misconceptions held by students. The second year's intervention was an instance of anticipating counterexplanations in advance and planning experiments to rule out the reinterpretations.

The science teacher can also use the post hoc approach to countering rejections and reinterpretations. Watson and Konicek (1990) observed some simple heat and temperature experiments carried out in a fourth-grade classroom. Students in the class believed that sweaters and hats are warm because they generate heat, like a heater. To test their idea, the students placed thermometers inside some sweaters and left them there for 15 minutes. Although the thermometers remained at room temperature, the students did not change their theory; they attributed the result to having left the thermometers in the sweaters for too short a time. Therefore, the students decided to leave the thermometers in the sweaters overnight. But when the children discovered that the thermometers were still at room temperature the next morning, they made additional reinterpretations, such as claiming that drafts of cold air had gotten in through the sweaters. To test this, the students tried sealing the sweaters up in plastic bags so that cold drafts could not interfere, but still the thermometers remained at room temperature. After several days of further experimentation, students began to run out of counterexplanations for the anomalous data. Watson and Konicek reported that when it was time to write down their explanations in journals, "Owen didn't know what to write, and Christian wrote simply, 'I don't know why'" (p. 682). At this point, the teacher suggested that perhaps the source of heat inside sweaters and hats was the human body, not the sweaters or hats themselves. This explanation led to another round of experimentation, and at least some of the children changed their theory. Thus, through a process of conducting multiple experiments that systematically ruled out, one by one, the children's reasons for rejecting or reinterpreting anomalous data, the teacher paved the way for theory change. This example also supports the notion that individuals will not change theories unless there is a plausible alternative.

Processing Strategies

The final set of factors that can affect an individual's response to anomalous data is the individual's strategies for processing the anomalous data. At present, we find only one strategy for which clear evidence exists: the strategy of processing evidence deeply (cf. Craik & Lockhart, 1972).

Deep Processing

Processing evidence deeply includes such mental processes as attending carefully to the contradictory information, attempting to understand the alternative theory, elaborating the relationships between the evidence and the competing theories, and considering the fullest available range of evidence (cf. Nickerson, 1991). Research in social psychology suggests that theory change is more likely when people process contradictory information deeply than when they do not (see Cooper & Croyle, 1984; Tesser & Shaffer, 1990). However, in practice people frequently fail to process contradictory information deeply; in particular, they attend much more to evidence that supports their beliefs than evidence that contradicts them (e.g., Galotti, 1989).

How can people be encouraged to process contradictory information deeply? One way to do it is through choosing an issue that is personally involving to the reasoner (Chaiken & Stangor, 1987; Tesser & Shaffer, 1990). An experiment by Petty and Cacioppo (1979) is typical: Undergraduates who supported lenient dormitory visitation policies were exposed to a persuasive message that argued for stricter policies. In the low-involvement condition, subjects were not personally involved with the issue; they were told that the policy proposal had been made at another college, not their own. In the high-involvement condition, subjects were told that the proposed change in visiting policies was being advocated at their own university. The persuasive message had no effect on low-involvement subjects, but it led high-involvement subjects to regard stricter visitation policies more favorably. Further research has established that this effect is mediated by more thorough processing of the contradictory arguments (Petty & Cacioppo, 1979, Experiment 2; Petty & Cacioppo, 1984; Petty, Cacioppo, & Goldman, 1981).

A second way to foster deep processing of contradictory information is to tell reasoners that they will have to justify their reasoning to other people (Chaiken, 1980; Kruglanski & Freund, 1983; Tetlock, 1983). In Chaiken's (1980) study, undergraduates were presented with messages that contradicted their prior beliefs. For example, subjects who believed that people need 8 hours of sleep per night were exposed to a persuasive message that asserted that people should sleep much less than 8 hours per night. Some subjects were told that they would discuss the issue at a later experimental session with their peers; other subjects were told that they would discuss an unrelated topic at a later experimental session.

The results showed that the subjects who expected to have to justify their opinions in a discussion with their peers processed the arguments more deeply and were more convinced by the arguments.

Thus, it seems clear that the processing strategies adopted by people for a particular reasoning task affect their response to anomalous data. If they are personally involved with the issue, or if they expect to have to justify their reasoning, people process anomalous information deeply and are more likely to change their theories. Otherwise, they are content to process the information superficially, and theory change is less likely.

We know of no studies that have examined whether deep processing affects how science students respond to anomalous data, but there is no reason to think that deep processing is not important in science education, as well. Students who are not motivated to process scientific evidence deeply are not likely to change their theories, or if they do change their theories, the change will be superficial, not involving a deep understanding of the new theory and why it is supported by the evidence. And it seems probable that deep processing goals can be aroused in science classrooms through personal involvement and through students knowing that they will have to justify their judgments.

Summary of Factors that Influence How People Respond to Anomalous Data

In this section we have discussed factors that affect individuals' responses to anomalous data. Here we provide a brief summary of the ground we have covered.

Four characteristics of prior knowledge influence people's responses to anomalous data. More entrenched beliefs lead to theory-preserving responses and make theory change more difficult. Ontological beliefs tend to be deeply entrenched, so that anomalous data that contradict these beliefs tend to produce theory-preserving responses. Some epistemological commitments, such as a commitment to consistency, foster theory change; others, such as a belief that science is a matter of memorizing facts, probably impede theory change. Background knowledge can, on one hand, facilitate rejection or reinterpretation and, on the other hand, facilitate theory change, depending on the particular content of the background knowledge.

Two characteristics of the alternative theory influence the response to anomalous data. The availability of a plausible alternative theory makes theory change, or at least peripheral theory change, more likely and theory-preserving responses less likely. A key to plausibility is an explanatory physical mechanism. It is desirable for the alternative theory to be intelligible as well as plausible, but this may not be strictly necessary to permit theory change. Finally, the better the alternative theory (in terms of its accuracy, scope, and consistency), the more likely theory change is.

Three characteristics of anomalous data influence the individual's response. More credible data are less likely to be rejected. Less ambiguous data are less likely to be reinterpreted. And multiple experiments can make both rejection and reinterpretation less likely.

Finally, we have identified one processing strategy that influences how people respond to anomalous data. Deep processing makes theory change more likely and can be enhanced in at least two ways: by fostering personal involvement in the issue and by ensuring that students know that they will have to justify their reasoning.

Implications for Science Instruction

To this point, we have discussed the seven forms of response to anomalous data and the factors that influence these forms of response. In this section we ask: What are the implications of our analyses for science instruction?

At first glance, it might seem that the teacher's task is to maximize the likelihood of theory change and minimize the likelihood of theory-preserving responses. But do educators really want students to change theories whenever they encounter anomalous data? Should a high school physics student disavow the laws of thermodynamics after reading a newspaper report stating that an inventor has developed a perpetual motion machine? Should a biology student abandon evolutionary theory after hearing about some creationist "data"? Obviously, it is frequently more rational to discredit anomalous data than to change theories: the teacher does not want to foster blind theory change but instead theory change that is rational and reflective.

In the following sections, we discuss ways in which teachers can foster *reflective* theory change. To do so, the teacher must orchestrate the same four clusters of factors that we discussed in the previous section: the students' prior knowledge, the alternative theory, the anomalous data, and the students' processing strategies. Table 3 presents 11 general instructional strategies that we hypothesize will foster reflective theory change. These strategies derive directly from the framework developed in the previous section.

In the following sections, we discuss each of the 11 general instructional strategies shown in Table 3, and we also discuss more specific instructional techniques that teachers may find helpful in implementing the strategies.

[Insert Table 3 about here.]

Influencing Prior Knowledge

Four of the 11 strategies in Table 3 are ways of influencing prior knowledge.

1. Reducing the Entrenchment of Students' Prior Theories

In attempting to reduce the entrenchment of the prior theory, it is important to identify those particular entrenched beliefs that are the *source* of the entrenchment of the theory as a whole. Consider an example from the domain of astronomy. Vosniadou and Brewer (1992) have found that many children possess a hollow-earth model of the earth; that is, the children believe that the earth is hollow, rather like a jack-o'-lantern, and people live on the flat bottom inside. A teacher might try to produce evidence to contradict this hollow-earth theory, such as photographs that show that there is no hole at the top of the earth. But what the teacher would be overlooking is the particular entrenched beliefs that underlie the hollow-earth model. Vosniadou and Brewer (1992) argue that the hollow-earth model is an attempt to reconcile the notion that the earth is round with the student's entrenched belief that things fall downward. Because things fall downward, it is inconceivable to the child that people could live on the outside of a spherical earth, because the people on the sides and bottom of the sphere would fall off; therefore, people must live inside at the bottom of the hollow sphere. Vosniadou (1992) argues that in order to lead the student to change the hollow-earth model, it is essential to address the entrenched belief that things fall downward. Before students will adopt the adult model of the earth's shape, they must be convinced that it is sensible to believe that people can live on the surface of the southern hemisphere without falling off.

Thus, to change an entrenched theory, it may be necessary to figure out precisely why the theory is entrenched, that is, to identify those crucial components of the theory that are most deeply entrenched. Without addressing these components, fundamental theory change may be very difficult.

2. Helping Students Construct Appropriate Ontological Categories

As we have noted earlier, theory change in some scientific domains requires a fundamental ontological shift in how basic phenomena are interpreted, as when a student must come to understand electrical current as an event or process rather than as a material substance (Chi, 1992). Chi (1992) proposes that the way to lead students through these ontological shifts is by explicit instruction: students should "be told that physics entities belong to a different ontological category" (p. 142). Then, as concepts such as heat and current are introduced one by one, teachers can help students understand how and why each concept fits into the ontological category *event* instead of the category *substance*. Students must then reassign the old concepts of heat and current to the new ontological category. Although this instructional approach seems plausible, it has not yet been tested empirically.

3. Fostering Appropriate Epistemological Commitments

There has been only a limited amount of research on the epistemological aspects of data evaluation and theory change. However, based on this research, we conjecture that reflective theory change is more likely if students' epistemology includes the following components:

a. An explicit understanding of the relationship between theory and evidence (Kuhn, 1989).

b. An understanding of the need for consistency among theoretical ideas and between theoretical ideas and data (Reif & Larkin, 1991; Strike & Posner, 1985).

c. An appreciation of the weakness of ad hoc changes to theories (Samarapungavan, 1992).

d. An active fair-mindedness in theory evaluation (Nickerson, 1991).

e. A willingness to change theories when warranted (Easley, 1990).

f. The belief that science applies to the everyday world as well as to laboratory data (Songer & Linn, 1991).

g. An understanding that science is a continuing process of debate about evolving theories rather than a static body of knowledge (cf. Easley, 1990).

There are, no doubt, other important epistemological commitments; these seven are only a subset of a larger set that is as yet unexplored.

How can these components of an epistemology be taught to students? One approach is that of *enculturation*. Discussing similar epistemological commitments in mathematics, Schoenfeld (1988) concludes:

> you don't develop this aesthetic simply by mastering the formal procedures of the domain. You certainly don't develop it by having it preached at you, in classic platitudes (e.g. "Mathematics helps you think."). To put things simply, you pick it up

> by internalizing it, that is, by living in a culture in which the appropriate values are reflected in the everyday practices of the culture. (p. 87)

In other words, to learn epistemological commitments appropriate to evaluating evidence and theories, students may need to participate in a community that regularly debates alternative theories, discusses responses to anomalous data, and evaluates evidence and theories. During this process of enculturation, students are like apprentices learning the craft of scientific reasoning, and teachers can use strategies of modeling (by thinking out loud in front of students), coaching, providing scaffolding and gradually withdrawing it, and reflecting upon the cognitive strategies used (Collins, Brown, & Newman, 1989).

There is some empirical support for the notion that enculturation methods can foster the development of epistemological commitments. In the domain of mathematics, Schoenfeld (1985, 1989) has presented evidence that an enculturation approach to instruction leads mathematics students to use cognitive strategies more like those of mathematics experts than those of novices. In the domain of science, Carey et al. (1989) developed a 3-week instructional unit blending an enculturation approach with some explicit instruction on the scientific method. As a result of this short intervention, students showed a marked increase in their understanding of the nature and purposes of scientific inquiry.

In order to help students understand that science involves a continuing process of theory development rather than a static body of knowledge, it may be important to give students opportunities to explore scientific theories without requiring that they reach a predetermined conclusion. Teachers might sometimes let students develop and assess alternative theories without telling them what scientists believe (Easley, 1990). Alternatively, students might consider which of two competing scientific theories from the history of science was better supported during the historical period of conflict. Or students could explore current scientific debates that are as yet unresolved, such as the debate about whether dinosaurs were warm-blooded or cold-blooded.

4. Helping Students Construct Needed Background Knowledge

Before students can even begin to evaluate a theory, they need a wealth of domain-specific background knowledge. For example, to offer even a novice's evaluation of the various theories of dinosaur extinction, students need knowledge about meteors, volcanoes, the composition of the earth's interior, the fossil record, geology, geochemistry, methods of measurement, and so on (cf. Chinn & Brewer, 1992a). In domains in which students observe or conduct laboratory experiments, background knowledge about laboratory techniques is needed for informed evaluation of any anomalous data.

In addition to domain-specific background knowledge, domain-general background knowledge can help promote reflective theory change. Examples of knowledge that can be applied across many different scientific domains include mathematics, statistical knowledge (including knowledge of how to interpret covariation data), and an understanding of experimentation.

Although transfer of knowledge is notoriously difficult to achieve through instruction, there is evidence that such domain-general knowledge can be taught in such a way that it does transfer to new situations (Bassok & Holyoak, 1989; Fong, Krantz, & Nisbett, 1986; Lehman, Lempert, & Nisbett, 1988; Nisbett, Fong, Lehman, & Cheng, 1987). Even brief training in statistical principles improves people's solutions on everyday reasoning problems related to those statistical principles (Nisbett et al., 1987). Moreover, Lehman et al. (1988) found that graduate training in psychology and in medicine greatly improved graduate students' performance on everyday reasoning tasks involving experimentation and statistics. The authors argued that graduate students' improvement could be attributed to a blend of formal training in experimental methodology and statistics with many opportunities to apply this training to the evaluation and conduct of actual research. Science instructors may want to consider creating similar conditions in the classroom, perhaps by explicitly teaching relevant domain-general background knowledge and then by giving students many opportunities to apply it to the evaluation of anomalous data and competing theories.

Introducing the Alternative Theory

Three of the 11 instructional strategies presented in Table 3 involve the role of alternative theories in instruction.

1. Introducing a Plausible Alternative Theory

We argued earlier that theory change is more likely when students are presented with an alternative theory that includes a plausible mechanism. It is not necessary, of course, that the teacher be the one who introduces the alternative theory; students may also learn about an alternative theory from texts, from computers, or from other students during class or small-group discussions. But if the goal of instruction is theory change, students need some kind of access to a plausible alternative theory.

Instead of presenting the alternative theory explicitly, is it possible to allow students to discover the alternative theory by themselves in a laboratory or a computer microworld? The empirical evidence on discovery suggests that if students are not given sufficient guidance, many of them will fail to discover the alternative theory. (This is also true of scientists. The history of science is filled with cases in which scientists failed to make important discoveries even though the relevant data were staring them in the face [see, e.g., Chi, 1992; Glasser, 1934].) Psychological research consistently shows that discovering scientific concepts and principles is very difficult. Both children (Dunbar & Klahr, 1989; Forman & Cazden, 1985; Schauble, 1990; Schauble, Klopfer, & Raghavan, 1991) and adults (Dunbar, 1989; Gorman, 1986, 1989; Tweney et al., 1980) find it difficult to invent hypotheses that adequately cover a domain of data. This is true even of relatively simple domains, where the range of possible hypotheses is both explicitly stated and circumscribed. For example, Schauble et al. (1991) found that many fifth and sixth graders failed to discover all the variables that influence the speed of model boats in a canal even though there were only four variables to be investigated. Presumably, when the to-be-discovered hypothesis requires the invention of entirely new concepts, discovery of the hypothesis is extremely difficult (cf. Chi, 1992). Thus, in an unguided discovery environment, in which no hints are given, many students will simply fail to come up with the accepted scientific theory.

However, a discovery approach can be effectively combined with explicit presentation of an alternative theory. For example, Burbules and Linn (1988) designed an instructional strategy for adolescents who incorrectly believed that the weight of objects that are denser than water determines how much water the objects displace. A period of experimentation led some students to the correct principle, but other students were unable to think of the correct principle on their own. These students needed to be told what the correct principle was. But once they were told, they readily adopted the new theory, and they were able to transfer it to novel problems.

An alternative to directly telling students about the accepted theory is to draw their attention to relevant dimensions that they might be neglecting (cf. Light & Perret-Clermont, 1989). For example, Hardiman, Pollatsek, and Well (1986) and Siegler (1976) found that subjects who failed to induce the product-moment rule of balancing objects on a balance beam benefitted by having the importance of distance pointed out to them. With this clear hint, many subjects were able to discover the rule.

There is good evidence, then, that theory change is facilitated by making the alternative theory available to students. Although unguided discovery may fail to promote theory change, a discovery environment can be effectively supplemented by presenting the alternative theory to learners who do not discover it on their own. It is also possible to point out relevant dimensions instead of presenting the alternative theory explicitly.

2. Making Sure That the Alternative Theory Is of High Quality

Regardless of how students finally learn about the scientifically accepted alternative theory, it is desirable that the alternative theory be of high quality, in terms of the criteria of accuracy, scope, and consistency. In one sense, this is not difficult for science instructors, because the alternative theory is an accepted scientific theory. But it should not be a superior theory only from the perspective of scientists; it should provide a better account of the data that students have available to them. For example, the instructor must deal with the problem that from the young child's point of view, a flat-earth theory provides a better account of data available to the child than does a spherical-earth theory. Thus, the quality of the alternative theory must be considered hand in hand with the range of data that the students know about.

3. Making Sure That the Alternative Theory Is Intelligible

As we discussed earlier, an intelligible alternative theory may not be strictly necessary for theory change, but it certainly is critical for reflective theory change. Students cannot evaluate theories rationally when they do not understand the alternative theory. As a first approximation, a theory can be made intelligible via analogies (Duit, 1991), pictorial conceptual models (Mayer, 1989), physical models (Vosniadou & Brewer, 1987), examples (cf. Chi & Bassok, 1989), and even direct exposition. A more refined understanding of the theory can be gained through the process of examining a series of anomalous data. A theory is intended to explain data, and as students progressively understand the relationship between a new theory and the data that support it, they can refine their understanding of the theory, even if they do not yet believe it.

Introducing Anomalous Data

Of the 11 general instructional strategies presented in Table 3, 3 center on enhancing the cogency of the anomalous data. Teachers may choose to present the anomalous data, or they may have students gather and present the data themselves.

Anomalous data are more likely to promote theory change when they are credible and unambiguous and when multiple lines of data are presented. By selecting multiple lines of credible, unambiguous data, the teacher may be able to make theory change more likely. However, we also believe that students should sometimes be exposed to less credible data, ambiguous data, and single lines of data. Through discussions, students might come to understand what counts as more convincing and less convincing data. This awareness of some general criteria for evaluating anomalous data may help protect them against blind theory change.

1. Making the Anomalous Data Credible

Students may view data as more credible if they understand that the data have been gathered according to accepted principles. As teachers and students discuss anomalous data, they might also discuss these principles and the extent to which the data collection procedure adhered to them.

Live demonstrations and hands-on experiences may enhance credibility. If computerized simulations of data are presented, students may need to be convinced that the simulation faithfully mimics reality. Replications might be used when it seems necessary.

Finally, teachers may want to appeal to real-world data that students already know about. This can help reduce compartmentalization, in addition to promoting theory change. Earlier we presented the example of the biology teacher who reminded students that their theory of transport across cell membranes must be able to account for poisons (Dreyfus et al., 1990). In this instance, it was immediately obvious to the students that their theory ought to be able to account for what they knew about poisons. In other instances, the teacher can appeal to data that students know about but do not realize are relevant. Brown (1992; Brown & Clement, 1989) used this approach in teaching students about how forces apply to a book resting on a table. The students incorrectly believed that the table did not exert an upward force on the book. To counter this idea, students were asked to consider the situation of holding a book up with their hand. In this situation, students' intuitions produced ready agreement that their hand exerted an upward force to keep the book from falling. Then students were led to consider a series of analogies that formed a "bridge" from this intuition to the target problem. Students considered the situation of a book resting on a spring and then a book resting on a springy plank of wood. By thus connecting the target situation to intuitions that they already possessed, many students came to understand that a table does exert an upward force on a book.

2. Avoiding Ambiguous Data

One way of making sure that data are unambiguous is to choose data that are perceptually obvious. Thus, in Stavy's (1987, 1991) research discussed earlier, the plainly visible blue iodine gas was more effective at promoting theory change than the invisible acetone gas. Beyond perceptual salience, whether or not data are ambiguous can be determined only by considering the particular configuration of theories held by students. Ambiguous data are ambiguous only with respect to the particular theories that are competing. Therefore, it appears desirable for the teacher to know what particular competing theories the children hold, so that appropriate, unambiguous anomalous data can be chosen.

3. Presenting Multiple Lines of Data When Necessary

Because a single experiment will often fail to convince doubters, introducing multiple lines of data may be helpful. Using one approach, a teacher might plan in advance an entire series of experiments in order to deflect anticipated grounds for rejecting or reinterpreting the data. Using a second approach, the teacher might simply plan a single experiment and then react to particular objections raised by students. For example, if students reject a live demonstration showing that two weights fall at equal speeds on the grounds that the distance that the weights fell was too short, the teacher could conduct the experiment again (or have the students conduct the experiment) using a greater distance.

Influencing Students' Processing Strategies

There is one general instructional strategy that involves influencing students' processing strategies.

Encouraging Deep Processing

It seems likely that the teacher can promote deep processing strategies by promoting issue involvement and requiring students to justify their reasoning. Issue involvement might be promoted by having students explain everyday experiences and solve everyday problems. Having students justify their reasoning should come naturally in an environment in which students are discussing competing theories for phenomena.

Instruction That Uses Anomalous Data

The analyses presented in this report provide insights into how to organize science instruction that uses anomalous data. Our analysis supports the use of a sequence of learning events such as the following:

1. Consider an physical scenario whose outcome is not known.

2. Predict the outcome.

3. Construct competing theoretical explanations to support the predictions.

4. Observe the outcome (anomalous data).

5. Modify competing theoretical explanations, if necessary.

6. Evaluate competing explanations.

7. Reiterate the preceding steps with different data.

When translated into an instructional procedure, this sequence of learning events corresponds to what has often been called *conceptual change instruction* or *teaching for conceptual change learning* (e.g., Roth & Anderson, 1988).

The learning sequence begins with students considering a physical scenario whose outcome is not yet known (e.g., the teacher could present an electrical circuit and ask what will happen when the switch is turned on). Then students predict what the outcome will be and justify their predictions with theoretical explanations. In a small-group or class discussion, different students will probably advance different explanations; if the resulting set of explanations does not include the accepted explanation, it's possible for the teacher to suggest it as another alternative. Students observe the outcome of the experimental situation, and then they evaluate the competing theories and the anomalous data in light of the observations that they have just made. They consider other relevant data as they make their evaluations. At the same time, the students refine their understanding of the competing theories in terms of how they must be adjusted to fit the new data.

There is a common variation on this sequence of learning events. In this variation, students do not make any predictions. Instead, they begin by considering a phenomenon whose outcome is already known (e.g., the teacher could present the electrical circuit with the switch already on and ask students to explain it, or the teacher could ask students to explain a known phenomenon, such as an electric light circuit in the home). Although students make no predictions, they still generate different explanations and weigh these explanations against the present data and other data previously considered.

The sequence of learning events is then repeated with different anomalous data. A complete unit on a particular theory might contain many repetitions of this learning sequence, with different anomalous data being presented and evaluated. The series of anomalous data does not only lead students toward theory change; it also helps them refine their understanding of the new theory. Because a crucial part of coming to understand a theory is understanding little by little how the theory explains an array of data, the reiterations of the sequence of learning events are crucial to developing an accurate understanding of the alternative theory.

When teachers want to focus less on helping students learn particular theories and more on helping them understand that science is a process of developing and evaluating theories, they can follow much the same procedure. However, instead of making sure that students have the alternative theory available and that the anomalous data converge to support the accepted theory, teachers might give students more freedom in constructing their own alternative theories and in designing their own series of experiments to test their theories.

Summary and Conclusions

In this report, we have argued that understanding how people respond to anomalous data is crucial to understanding the process of theory change. In the first section, we proposed that there are seven forms of response to anomalous data: (a) ignoring the anomalous data, (b) rejecting the data, (c) excluding the data from the current theory, (d) holding the data in abeyance, (e) reinterpreting the data, (f) making peripheral changes to the current theory, and (g) changing the theory. In the second section, we discussed factors that influence which of these responses an individual will choose when faced with anomalous data. In the third section, we discussed implications of our analysis for science instruction.

Although we have confined ourselves to science instruction in this report, we believe that the analysis presented here holds promise for areas of education besides science instruction. Some applications are obvious: Our analysis can be applied to modifying students' causal theories in social studies classes, such as theories about economics or social forces. It could also be applied to changing entrenched stereotypes; teachers could use the framework described to provide insights into why people hold racist beliefs and how these beliefs might be changed. Our analysis could be applied to the cognitions that underlie motivation. For example, the belief that intelligence is a fixed entity, which underlies some students' helpless responses in school (Dweck & Leggett, 1988), could be addressed with conceptual change techniques. Finally, our analysis might yield insights into teachers' thinking. Teachers have deep-seated beliefs about learning and instruction that affect what they do in the classroom (Kagan, 1992); our analysis can illuminate teachers' responses to information that contradicts their implicit theories.

For belief change to occur in any of these domains, it is important to understand how people respond to anomalous information, and it is crucial to understand the conditions that make reflective theory change more likely.

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Footnote

[1]We want to clarify our usage of three terms: *knowledge*, *beliefs*, and *theories*. In philosophy, the term *knowledge* has traditionally been taken to be justified true belief. However, we will use the word in a more general way to refer to the total set of beliefs held by an individual. We use the term *belief* to refer to any piece of knowledge within this knowledge base. *Theories* are collections of beliefs that have explanatory force. We use the term *belief* rather than some other term to emphasize the fallibility of the knowledge; scientific beliefs and other beliefs often turn out to be mistaken or only partially correct in light of later discoveries. The term *belief* does not imply that beliefs are based on careful reflection; our notion of belief includes unexamined assumptions, including what diSessa (1988) has called "p-prims."

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Table 1

Features of Each of the Seven Responses to Anomalous Data

	Features of the Response		
Type of response to anomalous data	Does the individual accept the data?	Does the individual explain the the data?	Does the individual change theories?
Ignoring	no	no	no
Rejecting	no	yes	no
Excluding	yes or maybe[a]	no	no
Abeyance	yes	not yet[b]	no
Reinterpreting	yes	yes	no
Peripheral change	yes	yes	yes, partly[c]
Theory change	yes	yes	yes[d]

[a]The individual may either accept the data as valid or remain agnostic about whether the data are valid.

[b]The individual expects that the data will be explainable by the current theory at some future date.

[c]Only beliefs in the protective belt are changed.

[d]Core beliefs are changed.

Table 2

Factors That Influence How People Respond to Anomalous Data

Characteristics of prior knowledge

1. Entrenchment of the prior theory
2. Ontological beliefs
3. Epistemological commitments
4. Background knowledge

Characteristics of new theory

1. Availability of a plausible alternative theory
2. Quality of the alternative theory

Characteristics of the anomalous data

1. Credibility
2. Ambiguity
3. Multiple data

Processing strategies

1. Deep processing

Table 3

Instructional Strategies for Promoting Reflective Theory Change

Influencing prior knowledge

1. Reduce the entrenchment of the students' prior theories.
2. Help students construct appropriate ontological categories.
3. Foster appropriate epistemological commitments.
4. Help students construct needed background knowledge.

Introducing the alternative theory

1. Introduce a plausible alternative theory.
2. Make sure that the alternative theory is of high quality.
3. Make sure that the alternative theory is intelligible.

Introducing anomalous data

1. Make the anomalous data credible.
2. Avoid ambiguous data.
3. Use multiple lines of data when necessary.

Influencing processing strategies

1. Encourage deep processing.

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