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CONCEPTUAL CHANGE IN SCIENCE AND IN SCIENCE EDUCATION*

ABSTRACT. There is substantial evidence that traditional instructional methods have not been successful in helping students to 'restructure' their commonsense conceptions and learn the conceptual structures of scientific theories. This paper argues that the nature of the changes and the kinds of reasoning required in a major conceptual restructuring of a representation of a domain are fundamentally the same in the discovery and in the learning processes. Understanding conceptual change as it occurs in science and in learning science will require the development of a common cognitive model of conceptual change. The historical construction of an inertial representation of motion is examined and the potential instructional implications of the case are explored.

INTRODUCTION

There is a growing body of literature in cognitive psychology and science education which demonstrates that students come to science classes with intuitive conceptions that differ fundamentally from scientific conceptions in specific domains (Clement 1983; Halloun and Hestenes 1985; McCloskey 1983; McDermott 1984; Viennot 1979; Vosniadou and Brewer 1986). This literature also shows that 'naive' or 'intuitive' conceptualizations of a domain, while not fully developed and integrated, interfere with learning science. For example, qualitative explanations about the behavior of bodies in motion provided by those who have had some formal training in mechanics show that the student preconceptions are highly resistant to instruction.

Recognition of these facts has led to the 'crucial insight' that "pre-existing conceptual structures need to be modified in the course of instruction" (Champagne, Klopfer and Anderson, pp. 1074–75). It is far from clear, however, how to modify the preexisting structures. Attempts to 'teach to' what are thought to be student preconceptions have met with limited success. To complicate matters, recent work has shown that it is possible to bring about local changes in belief about the motion of objects without substantively changing the underlying nonscientific conceptual structure (Ranney 1988). A major part of the problem in devising appropriate instructional strategies is that not enough is known of a specific nature about the character and content

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of student conceptual structures and of a general nature about the character and processes of restructuring.

While the primary source of specific information about student structures in a domain is psychological research that probes these structures, conceptual change as it has occurred in the history of science provides a valuable resource for gaining an understanding of the general issues of restructuring and, in some cases, may even aid the formation of hypotheses about the dimensions along which to probe student representations (see Nersessian and Resnick 1988). There is some awareness of this resource in the science education literature. Some investigators have noted tantalizing parallels between intuitive conceptions in certain domains, e.g., mechanics, electricity, astronomy, and historical prescientific conceptions (see, e.g., Clement 1983; Driver and Easley 1978; McCloskey 1983). Others have proposed that the restructuring required of science students is similar to that which occurs in scientific revolutions (Carey 1985; Clement 1983; Kuhn 1962, 1974). Such comments have, however, remained suggestive since there has been no systematic assessment of the degree to which conceptual change in science education corresponds to conceptual change in scientific revolutions. The detailed investigation required cannot, of course, be undertaken in this paper. What follows is an exploratory investigation of what science educators might learn from knowing about conceptual change as it has occurred in the history of science.

'ONTOGENY RECAPITULATES PHYLOGENY'

Two questions need to be raised at the outset: (1) What possible relationship is there between the content of intuitive representations of a domain and historical 'prescientific' representation? and (2) What possible relationship is there between the process of acquiring a scientific representation and that of its initial construction? It is clear that the learning process cannot straightforwardly recapitulate the historical process. Historical representations are not simply "generalizations from experience" (Clement 1983) and neither are student representations. Metaphysical, epistemological, and sociological factors play an important role in the formation of a representation, and these will be different for the two processes.

A plausible case can be made, however, for a more limited recapitulation. First, on the question of content, in domains that are experientially familiar to students and where they have thought about problems with certain phenomena (e.g., motion of objects, shape of earth, living things vs. non-living) there may be a significant degree of recapitulation in the content of the representation. This would account for the findings that some student's views "reflect analogies with historically held views" (Driver and Easley 1978, p. 80), such as the 'impetus' conception of force. Additionally, historical and student representations may exhibit similar characteristics. For example, the 'motion as process' conception of medieval theorists exhibits the time-dependent causal reasoning Larkin claims to be typical for novices (Larkin 1983; see also Wiser and Carey 1983, for a similar observation). However, any analogy will break down at the point where metaphysical, sociological, and technological considerations have bearing on the representational content. Just how much recapitulation of content there is can only be discerned by in-depth, domain-by-domain investigation. Such investigations should begin with those cases where strong similarities appear to exist in parts of the representations, make detailed comparisons of student representations with historical representations, and use the historical representation to help delimit the dimensions along which to investigate student representations further.

The second area of possible recapitulation is that of the processes employed in constructing a scientific representation. Knowledge of the process of constructing and communicating new scientific representations has the potential to yield important insights for science education. It is often overlooked that conceptual change in science is a learning process for scientists as well. An individual scientist or group must learn how to construct a particular kind of representation of a domain and then must instruct the rest of the community in the new representation. Students learning a scientific representation must also actively construct: they must form new concepts and new relations among existing concepts and integrate the new representation to such an extent that they can make use of it. The working hypothesis of this paper is that both the nature of the changes that need to be made in conceptual restructuring and the kinds of reasoning involved in the process of constructing a scientific representation are the same for scientists and students of science. That is, the cognitive dimension of the two processes is fundamentally the same.

Understanding conceptual change in science and science education will require, ultimately, the development of a common cognitive model of the acquisition of scientific knowledge. In this paper I will provide an overview of a major conceptual change in the history of science and suggest ways that knowledge of the kinds of changes and of the nature of the procedures for constructing a conceptual framework involved in this case could enhance our understanding of conceptual change in students and facilitate the development of instructional strategies.

CONCEPTUAL CHANGE IN SCIENCE: RESTRUCTURING FROM IMPETUS TO INERTIA

This section provides a summary of an analysis of a major conceptual change in the history of science. An account is given of the salient aspects of the conceptual change from medieval theories of motion to Newtonian mechanics. Although only one case is presented, other analyses support the points to be made here (Nersessian 1984; Thagard 1988). An important feature of the analysis provided here is that the changes in an entire conceptualization are examined. This stands in contrast to most research in cognitive development and learning and in history and philosophy of science in which only one concept is targeted for study. Examination of an entire conceptualization is necessary, however, for a full understanding of restructuring because major conceptual changes in science always involve making a number of coordinated changes.

Philosophers and historians have emphasized that the construction of the principle of inertia "constituted the essence of the transition from Greek and medieval thought to the incontestably modern science of Newton's *Principia*" (Shapere 1974; see also, Clagett 1959; Dijksterhuis 1950; Koyre 1978; and Westfall 1966). Only a slice of that transition will be captured here: from medieval philosophers to Galileo to Newton. The conceptual changes will be described and then the processes of change will be discussed.

DESCRIPTION OF THE HISTORICAL RESTRUCTURING

The principle of inertia, as formulated by Newton, reads as follows: "Every body perseveres in its state of being at rest or of uniform

motion in a right line except insofar as it is compelled to change its state by forces impressed upon it" (Newton 1687, p. 13, translation corrected by Floris Cohen). The problem it resolves is that of how an object continues in its motion after it has been separated from the source of its motion. This problem was troublesome, though not of central concern to medieval philosophers. For them it was only a minor subproblem of the problems concerning the nature of change. It only became a problem in its own right when Galileo and others attempted to support the Copernican hypotheses of the motion of the earth. That is, if the earth is in motion one needs to explain why its motion does not appear to affect the path of objects in free fall and projectiles. Constructing an inertial representation of motion required a major conceptual restructuring, involving, in particular, significant alterations of the concepts of 'motion', 'vacuum', and 'space' and the construction of a new concept of 'force', with 'gravity' as a kind of force, distinguished from a body's heaviness.

The conceptual structure of medieval theories of motion is in essence Aristotelian. The division between heavenly and earthly phenomena is central to the Aristotelian representation. Heavenly bodies have a different essence than earthly bodies and their motions presented no problem. The motion of the planets is eternal and 'natural', i.e., where 'natural motion' is that directed towards the natural place of a body and thus requiring no explanation for its continuation. Aristotle reasoned that the eternal natural motion of a spherical heavenly body should take the perfect geometrical form: a circle. Earthly or 'local' motion is a process of change that bodies undergo, much like that of an acorn growing into a tree. Thus, 'motion' and 'rest', which is the natural state of earthly bodies, are separate and opposing categories. Rest requires no explanation for its continuance, but all motion does. In Newtonian mechanics, however, 'motion' and 'rest' have the same ontological status: they are both states. It is a consequence of this that only changes in motion require an explanation.

Two local motions, 'violent' (e.g., projectile) and free fall, presented problems for medieval theorists. First, objects in free fall, although in natural motion since they are going towards their natural place, accelerate as they fall. There was no satisfactory explanation in the Aristotelian scheme as to why this should be so. Second, objects in violent motion do not immediately fall downward when they are

detached from their source of motion, but continue in the same direction for a while. Since a body in motion is undergoing change in opposition to its natural state of rest, continuing motion requires a continuing cause of motion. Aristotle's explanation of this phenomenon was that the 'mover', e.g., a hand, imparts a moving power to the air in its immediate vicinity and this power is transmitted from layer to layer of the air through which the body passes until the power is exhausted. This explanation seemed implausible to medieval thinkers for several reasons we need not go into here. A new concept, 'impetus', given its final formulation in the fourteenth century by Jean Buridan, was constructed to explain these motions. Impetus is something that is implanted within a body by the mover and keeps it moving until it is either used up or interfered with. This notion is the closest we get to 'force', i.e., to a dynamical explanation of the cause of the continuation of motion, in medieval mechanics. Unlike force in Newtonian mechanics, however, impetus is a property imparted to the body by the mover. In Newtonian mechanics, 'force' is a functional quantity (a relationship) that explains changes in motion. Newtonian forces are not properties of bodies; rather, they are relations between two or more bodies.

Three other changes are needed to construct an inertial representation of motion. In medieval mechanics, '*gravitas*' (literally, 'heaviness') is a constitutive property of bodies. That is, bodies have *gravitas* in the same way that they have extension. This contrasts with gravity, which in Newtonian physics is a force acting on bodies and is thus not a part of the constitution of bodies. As a force, it is a relation between bodies, not a property of bodies. This allows one to conceive of bodies that are not subject to gravity, which is a prerequisite for inertial motion, i.e., motion in the absence of all forces. Second, in the medieval theory, motion can only take place in 'occupied' space. However, allowing for the possibility of motion in a vacuum is necessary to the formulation of the principle of inertia, i.e., inertial motion is isolated from all matter and forces. Finally, for an object to continue indefinitely in motion in a straight line, space must be open and infinite, rather than finite and closed as was the case in medieval cosmology.

Although it is not possible to do a proper historical analysis of the formation of the principle of inertia, a look at the beginning of its development will be instructive. In his defense of the Copernican

hypothesis of the motion of the earth, Galileo challenged the Aristotelian distinctions between rest and motion and between natural and violent motions. By using thought experiments to show the relativity of motion, he demonstrates that it is not possible to distinguish clearly between rest and motion and, thus, that there are no grounds upon which to base an a priori ontological distinction between them. Rest and motion are merely contrary states and the state of being in motion does not bring about change in the body itself.

The Aristotelian distinction between natural and violent motion is based on what it is thought to be 'in the nature' of a body to do. For example, it is in the nature of planets to move in circles and in the nature of earthly bodies to seek rest. Violent motion is thus motion which opposes the nature of bodies. Galileo shows this distinction to be untenable by using thought experiments about motions that are both natural and violent and motions that are neither. As Galileo employs it, the natural-violent distinction marks the difference between motions that happen by themselves (e.g., free fall) and those requiring an agent (e.g., projectile). Thus, with the abandonment of the distinction between local and heavenly motion, the central concept of 'motion' and its kinds, 'natural' and 'violent', change their meaning in Galileo's theory. This was a crucial step in the formulation of the principle of inertia. Additionally, Galileo's analysis of free fall establishes that its uniform downward acceleration would take place only in a vacuum, and thus a vacuum becomes possible in nature.

Galileo did not formulate the principle of inertia. He came very close to formulating it, and it is not difficult to derive the principle from his notion. Descartes actually formulated it, but Newton was the first to incorporate it into a viable mechanical theory. Galileo did not construct the present-day principle in part because of his retention of some of the concepts of the medieval theory. The notion that 'heaviness' is a constitutive property of bodies is retained in his analysis. He also continued to hold that space is finite and closed. Because he believed this was required to support Copernican astronomy, circular motion continued to have special status in his theory. Perfect circular motion, such as that on a frictionless plane circling the center of the earth, would continue forever if unimpeded. However, such motion would only approximate Newtonian inertial motion at small distances.

Since Galileo concentrated on kinematics and not dynamics – i.e., his main concern was to describe motion rather than to provide an

account of its causes – it is difficult to ascertain if his correlate to 'force' is a property or a relation. In his analysis of free fall, 'heaviness' functions as 'force', i.e., "the dynamic effect of heaviness is the production of a uniform increase in the motion of a body" (Westfall 1966). But, again, heaviness is a property of bodies. 'Force' as we know it was formulated by Newton in analysis of the problem of impact. His struggle to articulate this concept is evident from his earliest notes, which reveal that he began with an impetus notion (Westfall) and some unclarities still exist in the *Principia*. It is in this work that the definitive formulation of the principle of inertia is given and is made the 'cornerstone' of the new physics. However, its introduction is preceded by several 'definitions' through which the conceptual components of the principle are given their requisite formulation.

REPRESENTATION OF THE HISTORICAL RESTRUCTURING

Figures 1–3 are concept maps of the salient parts of the conceptual structures of the three theories of motion under discussion. This knowledge representation system is introduced simply to facilitate analyses of the conceptual changes. As used here, the concept maps consist of:

(1) concept nodes: names enclosed in ellipses
(2) links between concepts:
  (a) kind links: straight lines, labelled "K"
  (b) property links: lines ending in arrows, labelled "Pr"
  (c) relation links: lines ending in arrows, labelled "R" or with a particular relation

The main advantage of using the concept maps is that they provide a visual display of the differences in the conceptual structures. They capture the idea of a conceptual structure as a network, exhibit the location of a concept in the network, and exhibit the nature of the changes and their effects throughout the network much more clearly than can be done with text alone. The main disadvantage is that not all the subtleties of a conceptual change can be captured without making the maps so complicated as to defeat the purpose of introducing them. For example, as drawn here, Figure 2 shows clearly that 'motion' has changed from a process to a state, but it is not clear from

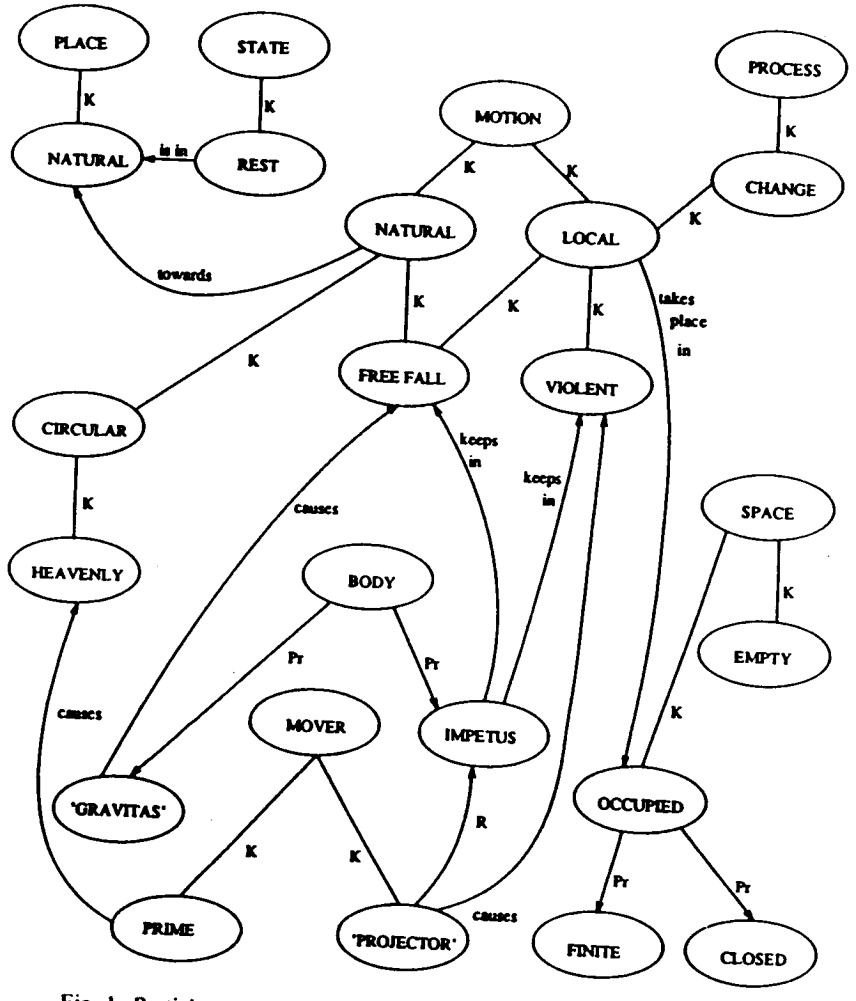

Fig. 1. Partial conceptual structure of the medieval theory of motion.

the diagram alone how 'violent' and 'natural' have changed their meaning. These changes could, of course, be captured by a series of smaller maps or by a more complex map. The maps in Figures 1–3 have been drawn to exhibit, primarily, the location of and interconnections among concepts in each representation of motion.

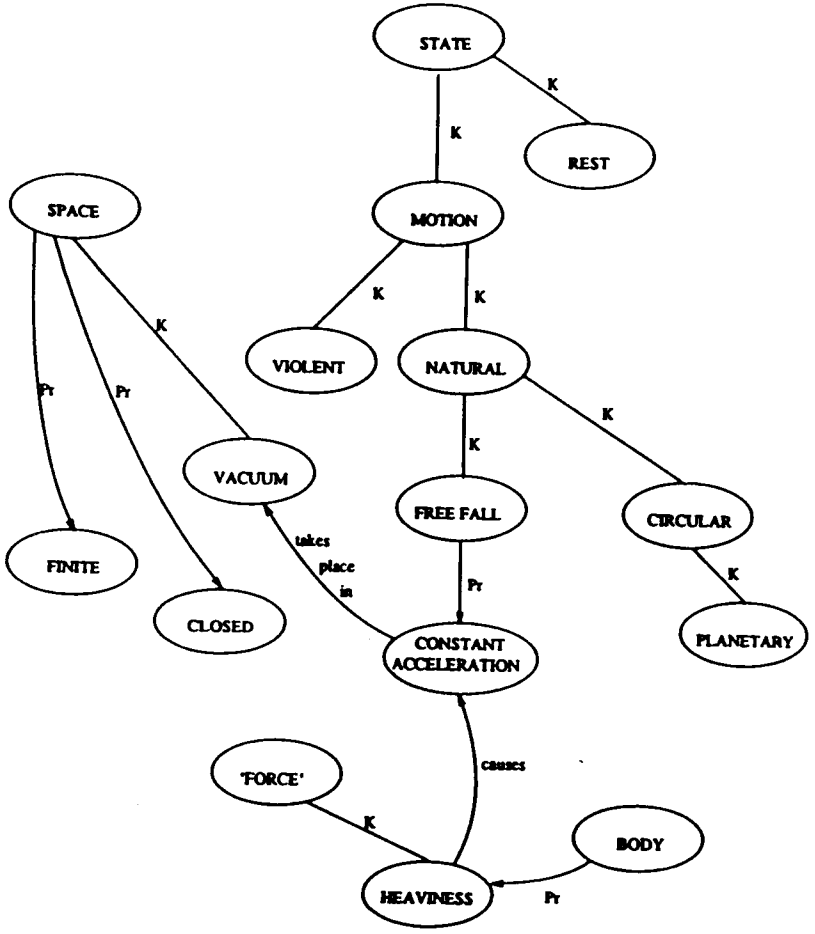

Fig. 2. Partial conceptual structure of the Galilean theory of motion.

As shown by Figures 1–3, the conceptual changes of this portion of the Scientific Revolution consist chiefly of changes in kind hierarchies, changes from properties to relations, and additions and deletions of concepts. There are a number of coordinate changes but they were constructed in piecemeal fashion, i.e., the changes do not entail one another. However, since the concepts are interconnected, some changes did force reevaluation at other points in the network; and this

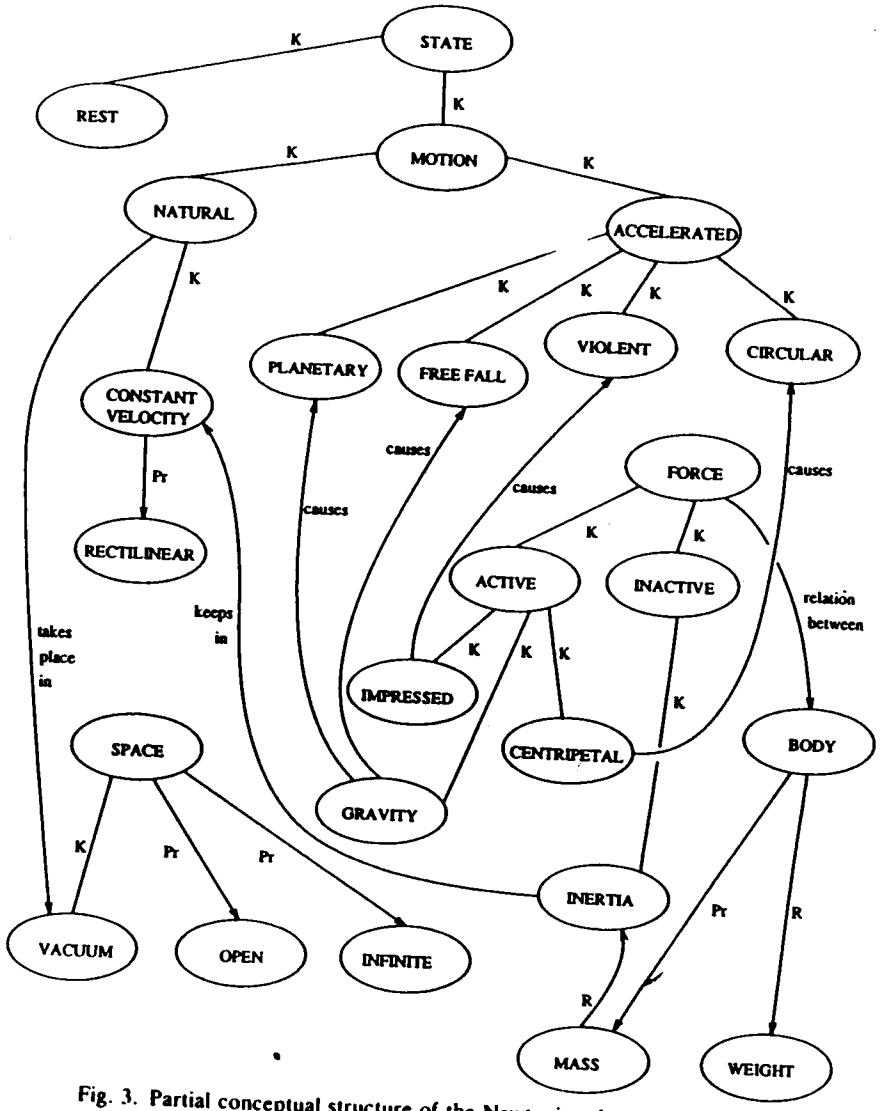

Fig. 3. Partial conceptual structure of the Newtonian theory of motion.

continued over the historical period in question until the new representations could be adjusted into a coherent framework.

CONSTRUCTING AND INSTRUCTING: THE GALILEAN REPRESENTATION

How were the conceptual changes made? Galileo will again be the focus of a brief answer to this question. We need to look at both how he constructed a new representation and how he instructed others in it. Although how much Galileo experimented is a subject of some controversy (see, e.g., Drake 1973; Koyré 1968; Naylor 1976; and Settle 1961) the 'discovery' process in this case was not mainly one of gathering new data and making inductive generalizations. Rather, it involved primarily the construction of abstract entities defined in terms of mathematical relations. With Galileo, what it means to be 'scientific' in the modern sense begins to be developed. It is this aspect of the development that makes examination of the Scientific Revolution potentially of great relevance to instruction, since in learning Newtonian mechanics students must usually also learn how to construct an abstract, mathematical representation of the physical world for the first time.

The central conceptual issue in the Scientific Revolution was the nature of the fit between mathematics and the physical world. The historian Koyré has called this issue the "mathematization of nature". 'Mathematization' is most clearly seen in the construction of the principle of inertia: "[W]hat it involves, strictly speaking, is the explanation of that which *exists* by reference to that which *does not exist*, which never exists, by reference even to that which *never could exist*" (Koyré 1978). On Koyré's analysis, to achieve 'mathematization' required that the qualitative, person-centered categories used by Aristotle to describe physical phenomena be replaced by idealized representations of phenomena, which he calls an "Archimedean mode of thought". By the end of the Scientific Revolution, the objects of that representation are completely quantifiable and interact according to mathematical laws. Motion of these objects takes place in a purely geometrical space. Thus, the central problem of this historical period was to work out the 'fit' between the representation and the world of experience. Aristotle believed that mathematics could not capture the 'essence' of physical phenomena, viz., 'becoming' and 'change'.

Medieval impetus theory, while attempting a coherent and systematic treatment of motion, was ultimately unsuccessful in its attempts to represent motion quantitatively because it retained the Aristotelian categories, which are unquantifiable. Galileo is the pivotal thinker in the transition to an idealized representation and, as Koyré notes, passed himself through Aristotelian to medieval to Archimedean modes of thought.

Although he did not formulate the modern principle of inertia, Galileo did make significant progress on the problem of how to construct a mathematical representation of physical phenomena. Under the influence of the recently translated work of Plato and Archimedes, he first struggled (1590) to quantify the Aristotelian/medieval categories, but was unable to achieve Archimedean precision. In his two major works (1632, 1638) he achieves success by refining two Archimedean techniques for constructing idealized representations of physical phenomena: thought experiment and limiting case analysis. A thought experiment is a mental model that allows one to manipulate aspects of a possible, though most often unrealizable, physical situation in one's imagination. Galileo uses them to expose inconsistencies in the medieval representation of motion and as 'data' to be quantified in constructing an alternative representation (see Manukian 1988). For example, Galileo's thought experiment of a heavy body and a lighter one tied together in free fall reveals the inconsistencies in the medieval belief that heavier bodies fall faster than lighter ones and shows the need to separate the heaviness of a body from its speed in quantifying free fall. In limiting case analyses, Galileo reasons from a physical situation (in some cases, experiments) to an idealized representation by abstracting specific physical dimensions from the phenomena, quantifying the idealization, and then arguing under what conditions the quantified representation is applicable to nature. For example, in analyzing the motion of a falling body, Galileo considers its motion in successively less dense media until he has abstracted the medium away entirely. It is only free fall in a vacuum that occurs with constant acceleration. Finally, the idealized representations of the thought experiments and limiting case analyses often facilitated Galileo's recognition of analogies between different phenomena, such as the motion of falling bodies and the motion of a pendulum. That is, idealized representations form abstract schemata common to different problems.

Galileo's endeavors to persuade others of his new theory of motion can be considered attempts at instruction. In instruction he employs some of the same methods he used in construction. He begins by putting forth the position of his opponents, then exposes the difficulties in the position, and finally leads the reader through the construction of a new representation of the situation under discussion. He uses both idealizations and experimental evidence to create conflict with their a priori expectations and then employs idealization techniques and analogical arguments to help the reader to develop the representation. Significantly, he does not simply present the premises and conclusions of his arguments but tries to get others to construct the representation. In so doing, his 'students' are helped to produce the representation in an integrated way that facilitates their use of it.

POTENTIAL INSTRUCTIONAL IMPLICATIONS OF HISTORICAL RESTRUCTURING

As stated at the outset this paper is exploratory in nature. Not enough is known about either conceptual change in science or the relationship between the discovery process and the learning process to come to any definite conclusions about how to generate effective instructional strategies. With this qualification in mind, some speculations are offered on possible instructional implications of conceptual change in science by probing aspects of the historical case study that seem potentially of relevance to learning. The following will be discussed:

(1) What makes restructuring so difficult?
(2) Through what kind of reasoning can students be led to construct a scientific representation of a domain?
(3) How might laboratory work in science be used in helping students change their preconceptions?

OBSTACLES TO RESTRUCTURING

It is well documented that student preconceptions are highly resistant to instruction. Scientific conceptual structures are equally resistant to change. In science at least three factors contribute to the difficulty. First, in all major conceptual changes in science, whole complexes of concepts have changed. These changes are largely independent, and

yet interconnected. They are independent in that emergence of a new concept or alteration of an existing one does not automatically lead scientists to see how to make the other changes that will eventuate in the new conceptual structure. At most the repercussions of change in one part of the conceptual network will spread throughout the network and will point to areas in need of revision. We see clearly what needed revision and why only in historical perspective. For example, Galileo's transforming motion from a process to a state did not force any particular revision in the cause of motion and any rethinking at all of the properties of space (see Figures 1 and 2). Local revisions, by themselves, do not force global changes. The instructional import of this is that in teaching a scientific conceptual structure, a number of concepts need to be targeted for revision at the same time and new concepts introduced in a coordinated fashion. Unlike the scientists who first constructed the conceptual framework, we can take advantage of hindsight and emphasize the relevant conceptual interconnections in instruction.

Second, it often happens that the same word is used in the old and new conceptual structure, but its meaning has changed significantly. As we have seen in the example developed here, 'motion', 'violent', and 'natural' have radically different meanings for medieval thinkers and for Galileo. Likewise for students and teachers. Calling attention to differences between student and scientific meanings of a word may be quite useful in the instructional process (see, e.g., Minstrell 1987). Several investigators have noted that in Newtonian mechanics what has been called the 'motion implies force' belief must be replaced with the belief that "acceleration [i.e., accelerated motion] implies force". But it has not been stressed sufficiently that since what students call 'motion' and 'force' differ fundamentally from the Newtonian conceptions, students cannot simply replace one belief with the other. They need to construct very different notions of 'motion' and 'force' before they can have Newtonian beliefs (see Nersessian and Resnick 1988). Indeed, by phrasing the student belief as 'motion implies force', we run the risk of obscuring this important fact.

Third, the history of theory change in science is largely the history of changes in ontology. The ontology of a theory determines what kinds of entities it claims to be about. At present there is no satisfactory account in either philosophy or psychology as to why changes in ontology should be more difficult than other kinds of changes.

Some candidate explanations are the following. First, ontological assumptions are at the center of a conceptual network and any changes in them will reverberate throughout the network. That is, one would expect that changes in ontological categories would force substantial changes throughout the network; though, as discussed above, what and how to change is far from automatic. Second, in cases where the change is from a commonsense ontology to a scientific ontology, abstract entities need to be constructed. In the case at hand, the actual entities of Newtonian mechanics exist only in mental models. For example, a Newtonian object is a point mass moving in an idealized Euclidean space. Additionally, changes from being a property to being a relation involve shifting from a concrete to an abstract representation. The difficulty here is that students must learn to think at a level of abstraction not customarily required for reasoning about commonsense objects. Thus, instruction in abstraction techniques might aid students in building the requisite scientific ontologies. Computer simulations, such as 'dyna-turtle' and 'microworlds' (di Sessa 1982; White and Horwitz 1987) might be used quite effectively to reinforce such instruction. They help the student to visualize how idealized objects would behave.

LEARNING BY CONSTRUCTION

Can the same kind of reasoning used in scientific discovery be fruitfully employed in science education? If learning a scientific representation involves active construction of the representation in a problem-solving process, then understanding how scientific concepts were developed in the first place will aid the development of instructional strategies. As stated at the outset, the working hypothesis of this paper is that there should be a single cognitive model for conceptual change in science and in learning science. Developing a scientific representation, whether initially or in learning, is a problem-solving process. The problem-solving strategies employed in science should be effective in science education as well.

What are the processes of scientific discovery? To begin with, although commonly used by philosophers and psychologists, 'discovery' is a bad way to characterize the process. 'Invention' would provide a better characterization, since scientific representations are constructed – they are made, not stumbled upon or found. Concept formation in

science requires such procedures as analogy, idealizations such as limiting case analysis and thought experiment, and use of imagistic representations. These are heuristic procedures, which while not algorithmic, are systematic and their use can be evaluated. These procedures comprise what has been called 'discovery argumentation'. It was this kind of argumentation that Galileo employed not only in his construction of the new representation of motion, but also in his attempts to convey it to others. By and large, traditional textbook arguments are 'justificatory'. That is, they present the student with reconstructed arguments that establish the correctness of the representation. Such arguments are useful when the conceptual structure of a science has been learned and we want to show why, e.g., a particular law holds. But what students need to do initially is to learn the concepts. Students are usually expected to learn the concepts of a theory like a language – by rote; and the 'vocabulary' of a physics text is often larger than the vocabulary that must be mastered in a language course (Tweney 1987). While much needs to be learned about how concepts are represented, it seems unlikely that memorizing 'definitions' of scientific concepts will enable a student to construct the requisite representation (Nersessian 1985 challenges the view that scientific concepts can be represented by definitions). What is proposed here is that there is good reason to believe that leading students through some of the same kinds of argumentation employed in the initial construction of a conceptual structure will prove more productive. Teachers do, of course, already make use of 'discovery argumentation' to some extent, but it needs to be incorporated more systematically into instruction designed specifically to teach the conceptual structure of a science.

RETHINKING SCIENCE LABS

The predominant ideology among science educators is that hands-on experience is at the heart of science learning. As important as laboratory experience is thought to be, there has been little systematic analysis of just what can be achieved in the science lab. In an attempt to provoke such analysis, two points will be made here. First, embedded in much of what is said about the need for students to have more laboratory experience is the implicit assumption that the 'the scientific method' involves primarily induction from data. This assumption has

been taken over from empiricist/positivist accounts of scientific method, and these have been severely challenged by contemporary philosophy of science. As seen in the case developed here, construction of the conceptual structure of a science is not entirely, and perhaps not even primarily, 'data driven'. The methods of construction do not consist of creating ever broader generalizations from data, but instead utilize heuristic techniques: analogies with other domains, thought experiments, etc.

Second, implicit also in the belief in the primacy of laboratory experience is the assumption that if students have the correct data, they will recognize when these conflict with their preconceptions. This assumes that 'the data' students reason about are 'pure', i.e., unaffected by their existing conceptions. But intuitive concepts do shape the data, although it has not been determined to just what extent (Champagne, Klopfer, and Gunstone 1982). And even if students recognize a conflict between their expectations and the data, they will often try to explain the data away, much as scientists often do in such cases.

These and other problems lead to the conclusion that some laboratory work should be directed explicitly towards conceptual instruction. Laboratory experiments, both real and computer-simulated, can be used with the explicit purpose of exposing areas of conflict with preconceptions, much as Galileo did with his experimental data and thought experiments. Computer labs can assist them in the construction of the conceptual framework of a science, and real labs can reinforce this by demonstrating to what extent the representation matches real phenomena.

CONCLUSION

The customary view of the interaction between history and philosophy of science and science education is that students and teachers of science should be taught historical developments and philosophy of science. While this is useful and important for many reasons, there is another potentially fruitful yet largely unexamined link that needs to be developed. This paper argues for the need to work towards the development of a common cognitive model of conceptual change: one that integrates the discovery and the learning processes. On this view history and philosophy of science and science education interact

through cognitive science. I have tried to give some indication of how understanding discovery is pertinent to learning. A full analysis will require the feedback of what we know about learning into analysis of the discovery process as well.

NOTE

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