Our recent research, much of it conducted with Hanne Andersen of Aarhus University in Denmark, has developed an approach to conceptual change in the history of science based on theories of concepts created by cognitive psychologists (Andersen, Barker, Chen, 2006). By using an empirical theory our work stands apart from that of most philosophers and historians of science, with the conspicuous exceptions of Ludwig Wittgenstein and Thomas S. Kuhn. The theories we have adopted are in fact direct empirical vindications of the accounts of concepts offered by Wittgenstein and Kuhn (Barker, Chen, Andersen, 2002).

In the present paper we sketch our general position and indicate some of the cases to which it has been successfully applied. Perhaps the most consequential result of our earlier work was the recognition that the cases we had treated successfully all employed a single type of conceptual structure, called an object concept. But one of the main cases we considered, Kepler’s innovations in astronomy, could only be adequately analyzed using a second and distinct type of conceptual structure known as a process concept. After introducing these ideas, we indicate their possible application to episodes from the history of science that we have not yet explored, including cognitive obstacles to the acceptance of Darwinism and climate change. We therefore offer these techniques as both a perspective on history and an approach to contemporary problems in public policy connected with science.

1. Object Concepts and Process Concepts

Recent research in cognitive psychology divides human concepts into two broad categories, object concepts and process concepts. These two types of concept represent two types of entity: objects that endure over time and processes that vary constantly.
Objects are temporally permanent—the totality of an object exists at any time during its life span. To conceptualize an object we typically focus on its spatial structure, outlining its shape, its parts and the relations between these parts (Barsalou, 1999). We can represent an object by means of its properties at a particular moment. Each of these properties will have a determinate value, and this value will be time-independent. Most familiar everyday concepts, and many important scientific concepts are of this type. Object concepts like planet, bird or element stand in contrast to process concepts, like the orbit of a planet, the evolution of a species, or the transmutation of an element like radium by radioactive decay into the element lead. Processes contain a temporal structure, that is, a chronological order. The totality of a process exists over the span of time that it takes to happen. At any given moment during a process’s life span, only one of its phases exists rather than the whole. It is impossible to capture a process by means of its properties at a particular moment, as the specific values of key properties will vary from moment to moment. Instead, we must trace the development of a process from its beginning to its end, examining the temporal and causal associations between past and present phases, as well as those between present and future phases. Thus, process concepts require a different mode of representation from object concepts.

We have successfully used frames to represent various object concepts in several historical studies including the development of typologies for birds during the Darwinian revolution, the discovery of nuclear fission in the 1930s, and the replacement of Ptolemy’s astronomical theories with the alternatives of Copernicus and Kepler (Andersen, Barker, Chen, 2006). However, during this work we recognized that the concept orbit of a planet, introduced by Kepler in the 1609 Astronomia nova, cannot be represented in this way. Paradoxically, although uniform circular motion appears to be a process, this key concept in astronomy before Kepler is an object concept: it can be represented by a set of properties that have fixed values over time. However, Kepler’s concept orbit of a planet is different. The representation of the concept must reflect continuous changes in the speed and direction of the planet’s motion. The key to representing the concept of an orbit is to capture the embedded chronological order, through representing the sequence of phases that occur along the dimension of time. The values of key properties, representing the physical state of a planet in a particular phase, are the causal conditions that are responsible for the physical state of the planet in a subsequent phase. But these key properties, like speed and distance from the sun, will not be constant over time but will vary from phase to phase. Thus, Kepler’s innovation is not just to abandon uniform circular motion as a fundamental concept in astronomy, but to introduce an entirely new class of concept that had not previously been employed in that science.

The recognition that major changes in science may correspond to the replacement of one type of concept by another completely different type raises many new possibilities. In addition to the Copernican revolution, there may be other important episodes in the history of science that took the form of transformations from an object to a process concept. One example is the optical revolution, during which one of the most profound
changes was the transformation of the concept of polarization (the phenomenon that rays of light exhibit different properties in different directions) from a spatial understanding to a temporal one, defining polarization as a process (Chen, 2003). Another example may be the Darwinian revolution, discussed below.

Earlier studies of revolutionary change in science, especially the work of Kuhn, were confined to examining changes in structures of object concepts. Even so Kuhn felt compelled to introduce the concept of incommensurability to represent the cognitive obstacles encountered when changing from one typology of objects to another. Like Kuhn we believe that under many circumstances there may be significant cognitive obstacles to such changes. Cognitive studies have shown that humans have an object bias, that is, a tendency to view processes as objects (Chen, 2007). Findings from developmental psychology indicate that human infants may have already developed a core system of object knowledge as early as 4 months of age and the persistence of this core system of object knowledge is responsible for the tendency to misapply knowledge of objects to processes. These findings have two important implications for understanding the history of science. First, there will be significant cognitive resistance to the replacement of an object concept by a process concept. Examples may be the resistance to Kepler’s innovations in astronomy and resistance to the concept of evolution in biology before Darwin. Second, there will be a persistent tendency to try to eliminate process concepts in favor of object concepts. Examples may include Ismael Boulliau’s attempt to retain the concept of an orbit but to reconstruct Kepler’s ellipses by compounding uniform circular motions (Boulliau, 1645), and the replacement of Maxwell’s no-substance theory of electric charge with the particulate theory of Lorentz (Buchwald, 1985). These biases may also have implications for ongoing controversies in science and public policy, including resistance to teaching evolution in American public schools, and confusion about climate change.

2. Cognitive Obstacles to the Darwinian Revolution

The Darwinian revolution is commonly understood as the introduction of the concept of evolution to explain the diversity of life on earth by Darwin, most importantly in his 1859 book *Origin of Species*. Historians now recognize that the Darwinian revolution had a complex and extended structure. Organic evolution had been proposed in other forms prior to Darwin, by Lamarck and Darwin’s grandfather Erasmus, for example, but had never been widely accepted. The publication of Darwin’s (1859) book led for the first time to the general acceptance of the idea that later species developed from earlier, different species. But Darwin’s mechanism for explaining change—natural selection—was generally rejected until well into the 20th century. The 19th century saw the acceptance of a form of Lamarck’s theory, followed by a period of confusion.
(Bowler, 1992), before the development of the ‘modern synthesis’ based on the work of figures like Dobzhansky (1937) and Huxley (1943).

Both inside and outside the scientific community, resistance to Darwinism has persistently been understood as based primarily on religious beliefs (Irvine, 1955; Bowler, 2007). From the viewpoint of cognitive analysis of concepts, however, the most striking feature of the Darwinian revolution is not the change in the status of religion or the deity, but rather the difference in type between the concepts employed in biology before and after Darwin. Before Darwin a species was a sharply defined group of objects, with fixed properties, and a fixed internal structure without significant variation. Species had no definite origin except the creation of the world. They occupied a fixed place in a static overall pattern of nature. And, apart from the end of the world, species had no foreseeable endpoint. Different species were presumed to occupy positions in a static pattern that made the whole optimal for them, or at least for the human race, conceived as the beneficiary of a divine providential plan (e.g. Paley, 1802).

The concepts just enumerated correspond to properties or attributes of the pre-Darwinian concept of species. They all have time independent values, and hence, in cognitive terms, species counts as an object concept. After Darwin the boundaries of species became less sharply drawn. The properties of members were no longer fixed because variation was continually adding and subtracting features through natural selection. New species emerged at a specifiable time through an ongoing process of evolution. The sum of all species was neither stable nor constant, and individual species might become extinct at any time. From a cognitive viewpoint it seems obvious that the concept of evolution is a process concept, and not an object concept. It may even be argued that the concept of species, originally an object concept, has also been transformed into a process concept by Darwin. Small changes in the properties and values representing individual species will take place continuously on Darwin’s model of variation and selection. As already indicated, modern research suggests that replacing an object concept with a process concept is an especially difficult cognitive task. Whatever the role of other factors in resistance to the scientific changes summarized under the title ‘Darwinian revolution’ (and we do not minimize the historical importance of these additional factors), the general replacement of object concepts by process concepts is an additional and previously unrecognized obstacle to the adoption of evolution in general and Darwin’s theory in particular.

3. Cognitive Obstacles to Understanding Climate Change

Many people, including highly educated people, mistakenly believe that we can stabilize CO₂ concentration in the atmosphere by continuously emitting CO₂ at the current rates. Cronin and Gonzalez (2007) believe that the widespread misunderstanding of climate change arises from a mental model that ignores change over time. Consider the changes
in the atmospheric ‘stock’ of CO₂ created by the inflow caused by processes like burning fossil fuels and the outflow caused by carbon removal processes like plant growth. In a ‘stock-flow’ system, the relationships between stock and flow are dynamic; the difference between inflow and outflow defines not the level but the change in level of the stock over time. The difference between inflow and outflow, the net flow, actually determines the rate of change of the stock level at a particular point of time. However, many people understand the relationships between stock and flow in a static manner, mistakenly believing that the difference between inflow and outflow actually defines the amount of the stock at a particular point of time. This ‘static’ mental model explains why some people believe that we can stabilize CO₂ concentration by continuously emitting at the current rates. If the difference between CO₂ emissions and CO₂ removal defines the level of CO₂ concentration, and if the amount of CO₂ removal is constant, then it would be logical—but incorrect—to conclude that keeping CO₂ emissions at the current rate can stabilize CO₂ concentration. People who think this way often favor a ‘wait and see’ approach to control of CO₂ emissions (Sterman, 2008). As in the cases of scientific change we have reviewed, we suggest that the difficulties here are cognitive: people are either resisting the use of a process concept or trying to treat a process (CO₂ accumulation) as if it was an object.

We suggest that the effects of the mental model described by Cronin and Gonzalez may be made worse by another form of object bias. Some misunderstanding of climate change may originate from treating the climate as if it were an object. If the climate is represented as an object, then its attributes will have constant values over time. Change will only occur by change in one of these attributes. If CO₂ is held constant, then it cannot produce changes in the object of which it is an attribute or property, that is, the climate. And if maintaining CO₂ emissions at current rates is mistakenly believed to hold CO₂ levels constant, then that too will be—mistakenly—believed to have no negative consequences for the climate. So this puzzling feature of the ‘wait and see’ position may perhaps be understood by recognizing that its supporters treat ‘climate’ as an object concept.

However, the earth’s climate is not an object but is a process, consisting of successions of transformations taking place over time. To understand climate change, we must focus on the temporal relations among the phases of the process over the whole span of time that it takes place. We must examine its development from the beginning to the end, investigating how the past has affected the present and how the present will affect the future. Capturing the temporal totality of climate change is the key to understand why keeping CO₂ emission at the current rate cannot stabilize CO₂ concentration. At first glance, we could have avoided the error through learning the basic principle of accumulation—to stabilize the amount of a stock, the inflow must be reduced to the level of outflow. At present, CO₂ emission exceeds CO₂ removal, so keeping emissions at current levels will lead to a continuous increase in the quantity of CO₂ in the atmosphere. However, there are worse difficulties that are only recognizable though considering the
temporal dimension of the problem. Even if we reduced the current level of emission to the current level of removal, we still could not stabilize CO₂ concentration in the future. To understand this apparent violation of the principle of accumulation, we must examine the whole process of CO₂ accumulation, particularly, the impact of the present climate conditions on the future. Studies have shown that as CO₂ level increases, the amount of CO₂ absorbed by oceans and biomass decreases. So, the same amount of CO₂ emission in the future is likely to cause more damage than has been observed in the past and present. Thus, to stabilize the effect of CO₂ concentration, a deep cut of CO₂ emission, a cut that goes beyond that required by the principle of accumulation, is necessary. This is a conclusion difficult to understand if we do not consider the temporal totality of climate change.

4. Conclusion

In this paper, we have indicated some resources that we believe are important for understanding historical change in science, as well as the contemporary state of science and its relations to public policy. We believe the distinction between object concepts and process concepts to be of fundamental importance. This distinction, which has not been applied before to the history of science, contributes to our understanding of what makes scientific revolutions revolutionary. Based on this distinction we have suggested that cognitive obstacles to conceptual change may originate from a bias to treat processes as objects and cognitive resistance to replacing an essentially static view of existence with a dynamic, process-based account. To remove these obstacles, we need to foster a fundamental transformation from the object-only ontological perspective to a new one that properly treats objects and processes as distinct kinds. This is not an easy task. To achieve this transformation, we need to shake off the influence of object bias and reexamine many of the assumptions, methods and practices that we have taken for granted. In many ways, this transformation is itself a revolutionary change.

REFERENCES


© 2009 John Wiley & Sons A/S.