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Hanne Andersen, Peter Barker and Xiang Chen
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Revolutions in Science and Science Studies

1.1 THE PLACE OF KUHN'S WORK IN STUDIES OF SCIENCE

Thomas Kuhn's *Structure of Scientific Revolutions* became one of the most influential books of the twentieth century, although its author suffered the fate of many prophets: he was ignored by the people he most hoped to influence. His technical terms became so widely known that a popular cartoonist could depict a newly hatched chick greeting the world with the cry "Oh! Wow! Paradigm shift!" (Taves 1998) and a best-selling guide to success in life and business would tell its readers, "[W]e need to understand our own 'paradigms' and how to make a 'paradigm shift'" (Covey 1990: 26). But there is no Kuhnian school of history, and many philosophers of science remain skeptical about his ideas. At the close of the twentieth century philosophers generally rejected paradigm shifts and normal science as useful categories for understanding scientific change and were still arguing about another key idea, incommensurability (Curd and Cover 1998; Hoyningen-Huene and Sankey 2001). Meanwhile Kuhn's emphasis on the historical variability of scientific standards and the role of research communities in scientific change was embraced by a new generation of sociologists of scientific knowledge. The new sociologists of science adopted Kuhn as a founding father, if not an intellectual guide: Kuhn's emphasis on the cognitive content of science was marginalized. Our aim in this book is to rectify this situation, by legitimizing the study of the cognitive content of science, in a new way, and providing the tools needed to write a defensible cognitive history of science. At the same time we hope to restore the ideas of conceptual revolutions and incommensurability to the central position they deserve in academic and practical studies of science.

Kuhn's notion of incommensurability provoked especially intense criticism from philosophers, who rejected his early account and largely ignored later attempts to dispel misunderstandings and refine or vindicate the notion through detailed studies of conceptual change in science (Hoyningen-Huene 1993; Kuhn 2000). There were many reasons for this; one of the most weighty was the conflict between mainstream English language philosophy and the theories of concepts developed by Kuhn and other cognitively inclined philosophers of science as the foundation for their work on scientific change. At the same time that Kuhn was refining his theory of concepts, empirical research in cognitive psychology and cognitive science began to undermine the classical theory of concepts, thus providing a new kind of support for Kuhn's philosophical account of science, and especially his account of scientific change. In this book we will use techniques from cognitive psychology and cognitive science to support and extend Kuhn's ideas on the nature of science. Our aim is to recover insights about revolutions and incommensurability in a form that will be usable by philosophers, historians, sociologists, and others who study science and its history.

1.2 REVOLUTIONS IN SCIENCE

Throughout this book we shall draw on detailed case studies of very different developments in the history of science. Two we will present in considerable detail, and two more briefly. We will present detailed examinations of the Copernican revolution, from the midsixteenth to the early seventeenth century, and of the discovery of nuclear fission during the third decade of the twentieth century. While the former has long been discussed as a key episode in the origins of modern science, the latter had equally important consequences inside and outside science. We will supplement these historical case studies with a briefer examination of developments in nineteenth-century ornithology, when the introduction of Darwin's theory led to changes in the classification of birds. We shall argue that in all of these cases, the conceptual structures develop in ways that display several revolutionary traits.

The discovery of nuclear fission was clearly a revolutionary development. In December 1938, Otto Hahn and Fritz Strassmann in Berlin performed an experiment with uranium that had unexpected results. They seemed to have created barium, an element with a nucleus scarcely half the size of uranium. Hahn and Strassmann asked the Austrian exile Lise Meitner for help, and assisted by her nephew, Otto Frisch, she explained how this strange thing could happen. Meitner and Frisch proposed that when struck by a neutron, the atomic nucleus was capable of disintegrating into two roughly equal fragments, releasing a great deal of energy and several additional neutrons. The practical implications of this discovery are well known (e.g., Flügge 1939). As word of Meitner and Frisch's interpretation spread, the international community of physicists rapidly accepted a new idea at radical variance with conventional wisdom.

The general acceptance of Meitner and Frisch's interpretation of the Berlin experiments also called into question an entire class of previously accepted research results that had seemed to establish the existence of a whole class of transuranic elements. These 'discoveries' had been made by Fermi's research group, and others, in earlier neutron bombardment experiments. After the general acceptance of Meitner and Frisch's proposal, all such experiments had to be reevaluated. In the opening stages of the Second World War, the previous results on transuranic elements were retracted, and the discovery of transuranics was recertified, on the basis of the work of Seaborg and Segrè, between 1939 and 1942 (Seaborg 1989).

The nature of the change that occurred in science in 1939 contrasts surprisingly with the events surrounding the supposed discovery of transuranic elements earlier in the decade. The technique of neutron bombardment had become available only after the discovery of the neutron in 1932. The use of a new technique to create completely new elements – elements not found in nature – might well have been expected to cause controversy. However, the Fermi group's claim to have created transuranic elements by neutron bombardment of uranium was accepted rapidly and without any major dislocations elsewhere in the structure of scientific knowledge.

To complicate matters further, the possibility that the nucleus could split into two relatively equal fragments had been suggested by a German scientist, Ida Noddack, in 1934, four years prior to the discovery of nuclear fission. Noddack suggested that "[w]hen heavy nuclei are bombarded by neutrons, it is conceivable that the nucleus breaks up into several large fragments, which would of course be isotopes of known elements" (Noddack 1934b). This suggestion was ignored or dismissed by the same community that rapidly accepted Meitner and Frisch's interpretation of the phenomena in 1939. Cognitive analysis can explain why the discovery of transuranic elements scarcely created a ripple on the surface of science, why the discovery of fission had so much more profound effects, and why the same community that rejected fission in 1934 accepted it in 1939.

Kuhn did not examine the discovery of fission in *The Structure of Scientific Revolutions*, although he did consider a wide range of the historical cases, most prominently the transition from the phlogiston theory to Lavoisier's oxygen theory of combustion, the replacement of Newtonian mechanics by Einstein's relativity theory, and, throughout the book, the replacement of Aristotle's physics and Ptolemy's astronomy by the Copernican view that the sun is the center of the planets' motions. His account of phlogiston chemistry provided a clear example of the kinds of changes that occurred during scientific revolutions, while his discussion of Einstein permitted a detailed examination of one of his major critical innovations, the concept of incommensurability. But the Copernican revolution proved problematic. It failed to conform to the general pattern of a revolution, preceded by a crisis, which in turn had been generated by an anomaly. Even though Kuhn believed at the time that astronomy in Copernicus' day was a good example of a crisis state (it is not: see Gingerich 1975 and Goldstein 1991), he could not point to an empirical anomaly of the type that he believed had motivated other revolutionary changes. He was therefore left in the ironic situation that his prototype scientific revolution, the Copernican revolution, did not really conform to the pattern that he was sketching for scientific revolutions in general. In this book, we shall argue that the Copernican revolution did precipitate revolutionary changes in the conceptual structure of astronomy, although these changes were not correctly located by Kuhn. We will argue that Copernicus' work can be seen as a minor variation on the conceptual structure in astronomy established by Claudius Ptolemy. Copernicus' work in astronomy, as opposed to cosmology, is not incommensurable with Ptolemy's. The revolutionary break occurs with Kepler, and it introduces not only a new conceptual structure that is incommensurable with the old one, but a new *type* of concept in astronomy.

Kuhn suggested that anomalies created the crises that caused revolutions. But an anomaly is not merely an experimental or observational failure. Rather it is a phenomenon that resists easy interpretation or classification according to accepted knowledge. We shall show that many important anomalies conform to a pattern illustrated as follows. Suppose that all the birds you have ever encountered resemble either chickens or ducks. How do you classify a bird that has the beak of a chicken, but webbed feet? When a bird called a screamer was discovered in South America during the nineteenth century, something very like this actually happened, and as a result the original categories used to classify birds had to be replaced with new and incompatible ones. We shall show how such responses to anomalies can be understood through a cognitive theory of concepts and categorization, and provide the basis for understanding incommensurability and revolutionary change.

1.3 THEORIES OF CONCEPTS

Between 1969 and 1994, Kuhn elaborated an account of scientific change in which the theory of concepts holds a central place. From the very first presentation of his work, Kuhn had introduced ideas that he found in the later writings of Wittgenstein on the nature of concepts and rule following. In developing his own account of concepts he extended Wittgenstein's account of family resemblance concepts. Like Kuhn's work in philosophy of science, Wittgenstein's account of concepts has been almost universally repudiated by professional philosophers in the English-speaking world. Kuhn's appropriation of Wittgenstein's account might have been no more than another footnote to the history of philosophy were it not for simultaneous developments in psychology. At about the same time, a successful revolution in psychology and allied fields – the Roschian revolution – replaced the classical theory of concepts with a range of new accounts that were remarkably similar to the theory Kuhn had developed.

1.3.1. The Classical Theory of Concepts

As we will use it in this book, the classical theory of concepts asserts that the application of a concept can be completely specified by discovering a set of necessary and sufficient conditions that define the objects falling under the concept. These necessary and sufficient conditions will be stated using other concepts and constitute what a philosopher would call the analysis of the concept, or a grammarian its definition. The secondary concepts introduced by the necessary and sufficient conditions specify certain features possessed by all objects falling under the original concept, but absent from objects that do not fall under that concept. In the most extreme case the list of necessary and sufficient conditions may indicate just one feature shared by all objects falling under the concept but absent from objects not falling under it. In more typical cases, the list of necessary and sufficient conditions, however long, may be taken as defining a single complex predicate or property shared by all objects falling under the concept.

Despite its historical durability, the classical theory of concepts is objectionable on practical, philosophical, and empirical grounds.

From a practical viewpoint, the main objection to the theory has been its intractability. It is more than two thousand years since the theory appeared in the works of Plato, but philosophers have failed to produce a single generally agreed analysis of any important concept that completely specifies the necessary and sufficient conditions of its application. Even relatively trivial cases in which such definitions appear possible remain open to challenge. Two favorite examples of concepts that can be completely analyzed by means of necessary and sufficient conditions are ‘triangle’ and ‘bachelor’. However, if ‘triangle’ is analyzed as ‘a plane figure bounded by three sides’, what becomes of triangles drawn on the surfaces of spheres or any of the other surfaces investigated in non-Euclidean geometry, beginning in the nineteenth century? If we accept that three-sided figures drawn on spherical or hyperbolic surfaces fall under the concept, can we also accept that figures drawn in a plane but bounded by nonstraight lines are triangles? And can the lines have breaks in them? A supporter of the classical theory might respond by adding new necessary and sufficient conditions to the original ones. A skeptic might respond that there is no visible end to this process.

The concept of a bachelor fares no better. Suppose we attempt to analyze ‘bachelor’ as ‘unmarried adult male’; then as Lakoff (1987) and others have pointed out this definition applies to many instances that we are otherwise reluctant to count as bachelors. Examples include gay men in permanent relationships, and other individuals, such as the head of the Roman Catholic Church, who are not in a position to marry (Coulson 2001). Although it is sometimes claimed as a virtue of the classical theory of concepts that it explains analytic inferences such as “Smith is unmarried; therefore Smith is a bachelor,” it may reasonably be objected that this inference is suspect unless we know that Smith is neither gay nor the pope. The same background information that controls our application of the concept in these cases may also operate when we draw inferences, undermining the supposed ‘analytic inferences’. What we need is a theory of concepts that incorporates this background information.

Difficulties of the sort just raised for ‘triangle’ and ‘bachelor’ may be attributed to the *open texture* of human concepts, an idea introduced by Wittgenstein (1953) and popularized in lectures by Friedrich Waismann (1965). This feature of language follows from the nature of the linkages between instances of concepts in natural languages, called by Wittgenstein *family resemblance*. In a famous example, Wittgenstein argued that many common concepts like ‘game’ could not be defined by means of necessary and sufficient conditions on the grounds that there was no single, common feature linking all objects falling under the concept. But these examples contribute to a more fundamental point: Wittgenstein argued for the priority of human practices, including linguistic practices, to the rules that may be devised to regulate or define them. The classical theory’s necessary and sufficient conditions, introduced in the analysis or definition of a concept, are enforced as rules to determine the application of the concept. But if, as Wittgenstein argues, practices are always prior to rules, no list of rules will completely determine the application of a concept.

Waismann and many others, including Kuhn, were inclined to see the problem as one of the future application of existing concepts. However successful we have been up to the present moment in specifying necessary and sufficient conditions for the application of a concept, there is, on this view, no guarantee that the next instance of the concept we encounter will not violate the norms specified in the analysis adopted so far. The original framers of the definition of a triangle could not foresee the advent of non-Euclidean geometry. But the difficulty is not just the result of new knowledge in mathematics or the sciences. Everyday situations provide evidence against the classical theory of concepts just as much as the novelties encountered in science: a patch of cloth may be a perfectly good triangle to a child learning the concept or an adult making a quilt, even though none of its three sides is a straight line and it will only repose in a plane after it is ironed. What is needed is a theory of concepts that functions equally well inside and outside the sciences.

Although the ideas of family resemblance and open texture became widely known after the publication of Wittgenstein's *Philosophical Investigations* in 1953, the dominant philosophical position in the English-speaking world remained some version of the classical theory. Defenders of classical theories found too many obscurities in Wittgenstein. But also, perhaps because his approach to philosophy strongly discouraged system building, no systematic alternative to the classical theory was articulated on the basis of Wittgenstein's work until Thomas Kuhn began to develop a theory of concepts, based on Wittgenstein's ideas, but informed by detailed studies of historical change in science.

At the same time, but separate from Kuhn's work, radical developments took place within psychology. These developments constitute the third, empirical objection to the classical theory. Beginning in the 1970s psychologists discovered that human concepts display graded structure. Specifically, human subjects readily rate instances of a given concept as better or worse examples of the concept. Before considering the empirical evidence for this important effect, let us briefly consider its implications as a philosophical counterargument to the classical theory. According to the classical theory all instances of a concept are equal. Every instance falls under the concept because it shares the same common features, those specified by the list of necessary and sufficient conditions that analyzes or defines the concept. So, if the classical theory is correct, there is no way to grade instances of a concept as better or worse examples of the concept. However, empirical studies show that human beings actually grade all instances as better or worse examples of the concept. Hence, the classical theory is false, and whatever human beings are doing when they use concepts does not involve lists of necessary and sufficient conditions.

1.3.2. The Roschian Revolution

Beginning in the early 1970s the American psychologist Eleanor Rosch made a series of studies examining the way in which individuals in many different situations and different cultures grouped objects into categories. Like Kuhn, she decided that no account based on category members sharing a single common feature was adequate to the empirical data she was collecting and concluded that analyses of concepts in terms of necessary and sufficient conditions were defective. The most compelling evidence that she gathered initially concerned the graded structure or typicality of concepts. Rosch found that individuals readily classified objects not only as members of particular categories but also as better or worse examples of the category. Rosch and her successors documented judgments of typicality worldwide among human groups as different as stone age tribes from New Guinea and undergraduate students from the United States.

In the judgment of Rosch's subjects, even objects that uncontroversially belonged to a category differed in how well they represented the category. To take a common example, for Westerners the best examples of the concept 'chair' turn out to be the kind we would expect to find at a dining table: they have four legs; a flat, hard seat, a straight back, and probably lack arms. Arm chairs, easy chairs, recliners, bar stools, three-legged stools, and modernist chairs supported on a single, central column are less good examples of the concept. Similar gradations in 'typicality' or 'goodness of example' appear in the case of natural objects. For Westerners a small bird with a sharp beak, a short neck, and a medium-sized body, like a blackbird, starling, or an American robin, is a good example of the concept. Those with longer legs, necks, or beaks are less good examples. For Asians, however, the best examples of 'bird' are likely to resemble ducks, geese, or swans: by contrast with the Western examples they have rounded beaks, long necks, and larger bodies (Barsalou 1992a: 176). Although Rosch demonstrated surprising agreement on typicality phenomena across cultures, for example, in the case of primary colors (writing as E. R. Heider 1972), the example of 'bird' shows that not all cultures agree on the same best example. Other research has shown that typicality may vary between individuals in a given context and in a single individual on different occasions (Barsalou 1987, 1989; Barsalou and Billman 1989).

What is universal, however, is the rating of particular instances of the concept as better or worse examples. We will refer to this phenomenon as the graded structure of a concept.

The existence of graded structure in human concepts has been demonstrated for a wide variety of different conceptual types, but most importantly for natural kinds and artifacts. Rosch originally demonstrated the existence of graded structures in categories for natural kinds like animals, birds, fish, and trees and artifacts like tools, clothing, and furniture. While these studies depended upon manipulating words, she obtained the same results in studies in which her subjects manipulated color samples or simple geometrical shapes. She concluded that both semantic and perceptual categories display graded structure (Heider 1972; Rosch 1973a,b; Rosch and Mervis 1975; Rosch et al. 1976). Other perceptual categories that display graded structure include human facial expressions (Ekman, Friesen, and Ellsworth 1972). At a more abstract level, notable studies established graded structures for categories including phrases used to designate spatial location (Erreich and Valian 1979), and to classify psychiatric conditions (Cantor, et al. 1980). Basic concepts in geometry and arithmetic were shown to display graded structures. Rosch's original work on the simplest geometrical figures was extended to polygons (Williams, Freyer, and Aiken 1977). A study arguing against Rosch's position ironically presented evidence that number concepts have graded structures (Armstrong, Gleitman, and Gleitman 1983; for a discussion see Lakoff 1987: 148–151). Graded structure was also demonstrated in categories that were completely artificial, or natural but completely novel. Homa and Vosburgh (1976) showed graded structure in artificial categories consisting of dot patterns, while Mervis and Pani (1980) showed the same thing for imaginary objects. Finally, Barsalou demonstrated typicality effects in categories that had been freshly constructed ad hoc, or in pursuit of specific short-term goals (Barsalou 1982, 1991).

Graded structure has also been shown to underlie performance across a wide variety of intellectual tasks (Barsalou 1992a: 175–177). Human subjects classify typical examples of a concept more rapidly than less typical or nontypical examples. Graded structure also appears in the operation of human memory: typical instances of a concept are retrieved from memory earlier and more rapidly than less typical instances. Graded structure influences language acquisition; children