8 Kuhn on Concepts and Categorization

PETER BARKER, XIANG CHEN,
AND HANNE ANDERSEN

8.1 INTRODUCTION

In Kuhn's account of the history of science the nature of concepts and conceptual change looms large. Kuhn found little to admire in contemporary philosophical accounts of science, and he also found himself at odds with the philosophical community on the theory of concepts. Consequently, in the course of developing his philosophical account of science he was also obliged to articulate a theory of concepts. One of the central ideas of his account, incommensurability, originated as a thesis about concepts. As his account matured, Kuhn came to formulate incommensurability as a thesis about taxonomies. The issue of categorization therefore emerges immediately from his account, with his theory of concepts providing the basis for the conceptual structures that he calls kind-hierarchies.

Kuhn's theory is not without precedent. It builds on the work of Wittgenstein, and also reflects Kuhn's early and profound exposure to Kant.[1] In a revealing interview near the end of his life Kuhn said simply, "I am a Kantian with movable categories" (Baltas, *et al.* 2000, p.264). Provided the categories are understood as Wittgensteinian family resemblance concepts, this is a valuable summary. As his philosophy of science developed, Kuhn focussed increasingly on the nature of scientific concepts, and his account of concepts gradually became the foundation from which he sought to vindicate his earlier claims on the development and change of scientific knowledge.

Another source for Kuhn's theory of concepts was his early reflection on science teaching which he came to believe created and sustained the consensus within the scientific community (Kuhn 1959, 1961; Andersen 2000a). Kuhn decided that science teaching is built almost exclusively on exemplary problems and concrete solutions rather than on abstract descriptions and definitions. The term "paradigm" entered Kuhn's work to denote these standard scientific problems.[2]

Within a given discipline, what the research problems "have in common is not that they satisfy some explicit or even some fully discoverable set of rules and assumptions that gives the tradition its character and hold upon the scientific mind. Instead, they may relate by resemblance and by modelling to one or another part of the scientific corpus which the community in question already recognized as among its established achievements" (Kuhn 1962/1970a, pp. 45f). The central point of Kuhn's argument was therefore that the kind of teaching found within the natural sciences confers the ability to recognize *resemblances* between novel problems and problems that have been solved before. But on Kuhn's view the recognition of resemblances was not limited to learning science. Soon he began to argue that language acquisition in general was based on learning to recognize resemblances. In his work after *Structure* Kuhn advanced an account of concepts based on similarity rather than rules (Kuhn 1970c, 1974, 1979); an account that developed gradually over the last three decades of his life (Andersen, 2001a).

In this chapter we describe the development of Kuhn's theory of concepts and categorization. We also consider the extent to which Kuhn's work on concepts, and related issues in his philosophy of science, receive independent support from recent research in psychology and cognitive science. In Section 2 we describe how Kuhn developed his theory by building on Wittgenstein's idea of family resemblance, but extending his account, especially in offering a solution to the problem of the "open texture." We next describe the way in which the accounts of Wittgenstein and Kuhn were independently supported by the work of psychologist Eleanor Rosch and her successors beginning in the 1970s. We then turn to two outstanding problems: first, whether incommensurability is a real phenomenon, and second, whether incommensurable conceptual structures are rationally comparable. In Section 3 we propose preliminary answers to these questions based on the theory of prototypes developed in cognitive psychology during the 1980s, although some limitations of the account are noted. In Section 4 we consider the frame model of concepts developed during the 1990s, which not only embodies all the features of Kuhn's original theory, but solves the outstanding problems of the prototype account, and naturally accommodates Kuhn's mature work on categorization and incommensurability. We present a detailed example from the history of taxonomy. Finally, in Section 5 we review Kuhn's original model of scientific change in the light of our results from contemporary theories of concepts and indicate various new directions.

8.2 KUHN'S THEORY OF CONCEPTS

Modern English-language philosophy continues a long tradition in accepting the view that concepts can be defined by a set of characteristics which are individually necessary and jointly sufficient for an object to be an instance of the defined concept. This view was attacked by Wittgenstein in his *Philosophical Investigations* published posthumously in 1953. Examining the concept "game" Wittgenstein showed that it might be impossible to find such a definition. Instead of a single common feature or features shared by all instances, there were only features common to subsets of instances, with many different features forming a network that ultimately linked them all, like the eyes, nose and hair-color linking different members of a single human family. Wittgenstein pointed out that instances of a concept might bear no more than a family resemblance to each other, with a complicated network of overlapping and crisscrossing relations linking them to other instances (Wittgenstein 1953, §66; cf. Kuhn 1962/1996, p. 45).

Kuhn first adopted Wittgenstein's notion of family resemblance in *The Structure of Scientific Revolutions* to argue that research problems are related by resemblance. But gradually Kuhn extended his argument to cover concepts in general, and in developing his account of concepts he gradually refined the treatment of family resemblance beyond the notion he had adopted from Wittgenstein.[3]

8.2.1 Concepts and family resemblance

According to Kuhn, teaching and learning depend upon examining similar or dissimilar features of some range of objects (Kuhn 1974, 1979). However, for the concepts involved in scientific research this process of concept acquisition is "excessively complex" (Kuhn 1974, p. 309). To present the main features of his account, Kuhn developed an example of the transmission of a set of simpler concepts: a child learning to distinguish waterfowl (Kuhn 1974).[4]

In this example, an adult familiar with the classification of waterfowl guides a child ("Johnny") through a series of ostensive acts until he learns to distinguish ducks, geese and swans. Johnny is shown various instances of all three concepts, being told for each instance whether it is a duck, a goose, or a swan. He is also encouraged to try to point out instances of the concepts. At the beginning of this process he will make mistakes, for example mistaking a goose for a swan. In such cases Johnny will be told the correct concept to apply to the instance pointed out. In other cases he ascribes the instance pointed out to the correct concept, and receives praise. After a number of these encounters Johnny has, in principle, acquired the ability to identify ducks, geese, and swans as competently as the person instructing him.

During the ostensive teaching Johnny has encountered a series of instances of the various waterfowl, and these instances have been examined in order to find features with respect to which they are similar or dissimilar. In this learning process, "the primary pedagogic tool is ostension. Phrases like 'all swans are white' may play a role, but they need not" (Kuhn 1974, p. 309). In this way a conceptual structure is established by grouping objects into similarity classes corresponding to the extension of concepts. It is an important feature of Kuhn's account that this grouping can be achieved solely by learning to identify similarities between objects within a particular similarity class and dissimilarities to objects ascribed to other similarity classes. Hence, for simple categories like "duck," "goose," and "swan," categories may be transmitted from one generation to the next solely by extracting similarity relations from the exemplars on exhibit.

Although everyday experience tells us that ostensive teaching is effective, it is important to understand its limits. At the end of the learning process Johnny and his teacher agree on the classification of available instances of waterfowl. This does not require that they possess identical conceptual structures. Each kind of waterfowl exhibits a range of features that may be used to judge it similar or dissimilar to other types. Obvious features are beak shape, leg length, neck length, color, and body size. For ostensive teaching to succeed it is not necessary that Johnny be taught to recognize exactly the same features that his teacher uses to distinguish ducks, geese and swans. All that is needed is that Johnny arrive at some set of features which permits him to group the waterfowl to the satisfaction of his teacher. Following a family resemblance account of concepts, it is easy to show that Johnny and his teacher may actually employ disjoint sets of features to classify waterfowl, yet agree in the classification of every instance they meet (Andersen, *et al.* 1996, Figure 3, p. 356). Ostensive teaching does not guarantee that all members of a community share the same conceptual structure. It only guarantees that they agree within the limits of the instances examined up to the present.

Kuhn claimed that, in principle, advanced scientific concepts are acquired by the same similarity-based process as everyday concepts; "[T]he same technique, if in a less pure form, is essential to the more abstract sciences as well" (Kuhn 1974, p. 313).[5] Where Johnny was presented with various waterfowl, and told whether they were ducks, geese, or swans, science students are presented with a problem situation after first being shown the appropriate expression of a law sketch through which the problem can be solved. Next, the students are presented with further problem situations and must try to assign the appropriate expression for themselves. In this process, the students examine the problems in order to find features with respect to which they are similar or dissimilar. For example, the law-sketch $\boldsymbol{F}=m\boldsymbol{a}$, Newton's second law of motion, applies to the problem of free fall in the form $mg=md^2s/dt^2$, to the problem of the simple pendulum in the form $mg \cdot sin\theta=-md^2s/dt^2$, and to more complex situations in still other forms. In learning scientific concepts the student is presented with a variety of problems which can be described by various forms of a law sketch. In this process, the student discovers a way to see each problem as *like* a previously encountered problem. Recognizing the resemblance, the student "can interrelate symbols and attach them to nature in the ways that have proved effective before. The law sketch, say $f=ma$, has functioned as a tool, informing the student what similarities to look for, signalling the gestalt in which the situation is to be seen" (Kuhn 1970a, p. 189). A conceptual structure is established by grouping problem situations into similarity classes corresponding to the various expressions of the law sketch. As Kuhn put it: "The resultant ability to see a variety of situations as like each other … is, I think, the main thing a student acquires by doing exemplary problems…" (Kuhn 1970a, p.189).

8.2.2 The importance of dissimilarity

Since we can always find *some* resemblance between instances of one concept and those of another, the objection is often raised that a family resemblance account does not suffice to limit the extension of concepts (Andersen 2000b, 2001b). Kuhn recognized this problem (Kuhn 1974, p. 307; similarly Kuhn 1970a, p. 200), but suggested that it could be solved by including among a concept's constitutive relations not only similarities between members of the same class, but also dissimilarities to members of other classes: "[N]ote that what I have here been calling a similarity relation depends not only on likeness to other members of the same class but also on difference from the members of other classes. ... Failure to notice that the similarity relation appropriate to determination of membership in natural families must be triadic rather than diadic has, I believe, created some unnecessary philosophical problems ... " (Kuhn 1976, p. 199).

The dissimilarity relation which Kuhn introduced here is not a relation between the instances of arbitrary pairs of concepts, but a relation between instances of concepts in a *contrast set*, that is, a set of concepts which are all subordinates to the same superordinate concept (cf. Kuhn 1983a, p. 682; 1991, p. 4; 1993, pp. 317f). For example, the concepts "duck," "goose," and "swan" are all subordinates to the superordinate concept "waterfowl."[6] Since they are all subordinates to the same superordinate concept, such contrasting concepts together form a family resemblance concept at the superordinate level, and their instances may therefore be assumed to be more similar to each other than to instances of concepts outside the contrast set. For example, ducks, geese, and swans together form a family resemblance category of waterfowl whose members resemble each other more than they resemble members of contrasting categories such as songbirds and game birds. Kuhn's emphasis on the importance of dissimilarity relations therefore serves to avoid the problem that instances of different but highly similar categories might be mistaken for each other, and leads to the view that contrasting concepts must always be learned together: "Establishing the referent of a natural-kind term requires exposure not only to varied members of that kind but also to members of others – to individuals, that is, to which the term might otherwise have been mistakenly applied" (Kuhn 1979, p. 413).

Obviously, this analysis can be extended to new superordinate and subordinate levels. Just as the superordinate concept "waterfowl" can be divided into the contrasting subordinates "duck," "goose" and "swan," so too each of the subordinate concepts can be further subdivided into the particular species of ducks or geese or swans. The hierarchical conceptual structure that arises is one in which a general category decomposes into more specific categories that may again decompose into yet more specific categories, in other words a taxonomy. Drawing on the dissimilarity between members of contrasting concepts, family resemblance therefore becomes tied to taxonomies. Kuhn never stated this argument explicitly, but only noted that "[A] fuller discussion of resemblance between members of a natural family would have to allow for hierarchies of natural families with resemblance relations between families at the higher level" (Kuhn 1970b, p. 17, fn. 1).

However, Kuhn also realized that the in-principle problem that anything is similar to anything else in some respect would only be solved by the use of contrast sets if the dissimilarity relations between objects were of a specific kind. Kuhn admitted that if the chains of similarity relations developed gradually and continuously it would indeed be necessary to define where the extension of the one concept ended and the extension of the contrasting concept began: "Only if the families we named overlapped and merged gradually into one another – only, that is, if there were no *natural* families – would our success in identifying and naming provide evidence for a set of common characteristics corresponding to each of the class names we employ" (Kuhn 1962/1996, p. 45). He therefore argued that the possibility of classifying objects into family resemblance classes depends on an "empty perceptual space between the families to be discriminated" (Kuhn 1970a, p. 197, fn. 14; similarly Kuhn, *et al.* 1974, pp. 508f.).[7]

By the early 1970s Kuhn had established the foundations of an account of concepts that shared many features of Wittgenstein's family resemblance view, and extended into new areas with the explicit discussion of dissimilarity relations and empty perceptual space. These ideas might well have languished in the obscurity to which Wittgenstein's proposals had been consigned by analytic philosophers, but for the unexpected appearance of new support for family resemblance theories among psychologists.

8.2.3 The empirical vindication of the family resemblance account

During the 1970s psychologists almost universally rejected the traditional view that concepts can be defined by necessary and sufficient conditions, on the basis of research begun by Eleanor Rosch and her collaborators (Rosch 1973a,b; Rosch and Mervis 1975). The single strongest piece of evidence against the traditional view is the demonstration of graded structure as a universal feature of human concepts.

It is a consequence of the traditional view that it makes all instances of a concept equal. All objects falling under a concept do so in virtue of sharing the same list of features, and therefore all are equal as instances of the concept. Consequently, it makes no sense to suggest that a particular object is a better example of the concept than another. However, empirical research shows quite the opposite. Human beings actually grade instances as good or bad examples of the concept. This variation in the instances' "goodness of example" is called the concept's "graded structure".

In experiments using human subjects as diverse as stone-age New Guinea tribes people and North American university students, Rosch and her collaborators showed that all concepts show graded structures (Rosch 1972 (writing as E. R. Heider), 1973a, 1973b; Rosch and Mervis 1975). Her initial data demonstrated graded structure in everyday perceptual categories for colors and geometrical shapes, and semantic categories for natural objects like birds, animals, trees and fish, and artefacts like furniture, clothing and tools. Psychologists all over the world replicated these results for natural categories, including facial expressions (Ekman, *et al.* 1972), locatives (Erreich and Valian 1979), psychiatric classifications (Cantor, *et al.* 1980), polygons

(Williams, *et al.* 1977), and numbers (Armstrong, *et al.* 1983) and artificial categories consisting of dot patterns (Homa and Vosburgh 1976) or imaginary objects (Mervis and Pani 1980), ad hoc categories (Barsalou 1982) and goal derived categories (Barsalou 1991). The existence of these graded structures showed the untenability of the earlier view that all objects falling under a concept are equally good instances of the concept, and hence the traditional view that concepts can be defined through necessary and sufficient conditions. As these results became known, the psychological community accepted graded structure as a universal feature of real human concepts, an event sometimes referred to as "the Roschian revolution."

Rosch herself recognized the connection between the new results in psychology and Wittgenstein's family resemblance account of concepts. At the same time Kuhn was developing his own version of the account specifically to understand science. As the new work on concepts by Rosch's successors developed during the next two decades Kuhn was also developing his own account. The two theories converged and their mutual support was recognized in the 1990s (Andersen, *et al.* 1996; Chen, *et al.* 1998). Although psychologists have developed a number of different models of human concepts consistent with Rosch's empirical findings, it would be premature to insist on the total adequacy of any one model (including those discussed below). However it is clear that any adequate model of human concepts must accommodate the phenomenon of graded structure and acknowledge its universality. Hence, at this moment in history, any account of human concepts consistent with empirical findings in psychology must provide conceptual resources equivalent of those available in the family resemblance account developed by Kuhn, and these resources will lead to the same results: necessary-and-sufficient condition definitions of concepts will be impossible, there will be no single common feature or list of features linking all instances of a concept, and, as Kuhn pointed out, it remains permanently possible that individuals within the a single community will employ disjoint features to successfully classify instances into existing categories.

8.3 KUHN'S THEORY OF CATEGORIZATION

8.3.1 Taxonomic change and local incommensurability

As Kuhn's theory of concepts developed it influenced other aspects of his account of historical change in science, especially the account of incommensurability, perhaps the most important and controversial concept in his account of science (Hoyningen-Huene 1993; Sankey 1994; Hoyningen-Huene, *et al.* 1996; Chen 1997). Incommensurability is a key feature of the conceptual changes that occur during revolutions. In *Structure* Kuhn used gestalt shifts as an analogy to illustrate incommensurability: scientists see things in an entirely different way after a revolution, as if shifting between views of an ambiguous figure (for example Wittgenstein's duck-rabbit), or suddenly wearing glasses with inverting lenses (Kuhn 1962/1996, pp. 122-126). From the metaphorical description of gestalt shifts, many readers of Kuhn concluded that he believed that paradigms were not comparable, and they consequently charged Kuhn with relativism. However, Kuhn has repeatedly claimed that these charges represent misunderstandings and that incommensurability allows rational comparisons of successive paradigms (Kuhn 1991, p. 3; Kuhn 1989, p. 23; Kuhn 1983a, p. 670; Hoyningen-Huene 1993, pp. 206-222).

To show the possibility of rational comparison, Kuhn made several revisions in his later explications of incommensurability. He dropped the gestalt analogy, abandoning the perceptual interpretation as well as the implication that revolutionary changes are instantaneous. He instead developed a metaphor based on language: during scientific revolutions, scientists experience translation difficulties when they discuss concepts from a different paradigm, as if they were dealing with a foreign language. Incommensurability was confined to changes in the meaning of concepts, and became a sort of untranslatability (Kuhn 1970a, p. 198; Hoyningen-Huene 1993, pp. 64-130).

In a dozen articles written during the late 1980s and the early 1990s, Kuhn offered a new account of incommensurability, which localized meaning change to a restricted class of kind terms.[8] These kind terms, together with their interconnections, form the taxonomy that classifies the entities studied in a particular scientific field. During a taxonomic change, some kind terms from the old taxonomy are preserved. But at the same time some new kind terms are added, some old ones are deleted, and many others are rearranged in different ways. To make sure that no two kind terms "may overlap in their referents unless they are related as species to genus," systematic regrouping of the referents to which the kind terms refer becomes necessary (Kuhn 1991, p. 4).[9] Sometimes referents previously regarded as quite unlike need to be grouped together, while referents of some single term in the old taxonomy have to be divided between different ones. These changes "affect not just the referents of an individual term but of an interrelated set of terms between which the preexisting population is redistributed" (Kuhn 1989, p. 31). Since such redistribution always involves more than one kind term and since kind terms are always interdefined, taxonomic change cannot be purely local.

On the other hand, because meaning change happens only in a very restricted class of terms, there always exist unchanged concepts that may be used as a basis for rational comparison between rival paradigms. Through the localization of incommensurability, Kuhn hoped to deflect the charge of relativism. If we consider these ideas from the viewpoint of cognitive science, extending the approach taken in our previous section, we find again that research on the nature of concepts in psychology and in cognitive science clarifies the cognitive phenomenon of incommensurability and lends additional support to Kuhn's position.

8.3.2 A prototype model of local incommensurability

According to Kuhn, incommensurability is directly caused by changes of conceptual structure, in particular, by changes of similarity relations (Kuhn 1970a, p. 200). For example, the incommensurability between Ptolemaic and Copernican astronomy, characterized by the meaning change of some key categories, was a direct result of conflicting classifications of the same objects into different similarity sets. Ptolemaic astronomers grouped the sun, moon, and Mars into one similarity set, “planet,” while Copernicans classified them into three different categories.

But how are changes of conceptual structure brought about? Any answer will depend upon adopting an account of human concepts. A popular account of concepts available in both contemporary philosophy and cognitive sciences is the so-called feature-list model, which characterizes people’s knowledge of a concept as a list of independent features. In the previous section we have examined the problems of a particular version of the feature-list model -- the classical account that concepts are defined by a set of necessary and sufficient conditions. Rather than specifying concepts by definitions, more recent feature-list accounts represent concepts by prototypes (Barsalou 1985; Barsalou 1987; Barsalou 1990; Homa 1984; Smith and Medin 1981). A prototype is a typical concept representation, which includes a list of features most likely to occur across the exemplars of the concept. In the process of categorization, we regard those referents with features that are highly similar to this list as typical, those less similar as moderately typical, and referents with dissimilar features as atypical. The prototype of the concept “chair,” for example, includes such features as the number of legs, the type of back, and construction materials, yielding (for US or European informants) a representation very similar to the four-legged straight backed kind often seen in a dining room. Other kinds of chairs, such as modernistic single-pedestal armchairs, are less typical, and barstools are atypical. These different degrees in typicality constitute the graded structure of the concept.

Representing concepts by prototypes can provide a dynamic account of concept formation. According to Barsalou, for example, prototypes are constructed in working memory, but the information contained in prototypes comes from a knowledge base in long-term memory (Barsalou and Sewell 1984, pp. 36-46; Barsalou 1987). The knowledge base for a concept may contain a tremendous amount of information, but only a small fraction of the information in the knowledge base is used to formulate a prototype in a specific situation. The cultural or theoretical stereotype that people have adopted influences which pieces of information in the knowledge base are activated and incorporated into the prototype in a given situation. Consequently, even people using similar knowledge bases may construct different prototypes for the same concept due to different stereotypes. In this way, the prototype account illustrates the critical role of established knowledge, a central point of Kuhn's theory of scientific revolutions.

The impact of stereotypes on individual concepts has been demonstrated empirically. In a psychological experiment conducted by Barsalou and Sewell in 1984, for example, subjects were asked to generate the prototype of a specific concept according to the cultural perspective assigned to them. The results show that those who took an American cultural perspective constructed a prototype of "bird" similar to robins, and regarded swans as only moderately typical, while those who took a Chinese cultural perspective developed a prototype of "bird" similar to swans, and regarded robins as less typical (Barsalou and Sewell 1984, pp. 15-26).

Although the impact of stereotypes is localized in individual concepts, the consequences of these local changes are holistic. First, a different prototype will produce a different graded structure for the concept, which includes different good examples, different moderately good examples, and perhaps different atypical examples. The similarity and dissimilarity relations will now attach to a totally different pattern of features. Moreover, as indicated in the previous section, similarity and dissimilarity relations also define the connections between a concept and the others in the same contrast set. The effects of changing a prototype thus can reach the whole contrast set. For example, if the prototype of "bird" is altered from robins to bats, the prototype of "mammal," which belongs to the same contrast set, also needs to be changed. If not, many examples of "mammal" would become notably similar to the prototype of “bird,” and the overlap between “bird” and “mammal” could jeopardize the category scheme. In this way, changing the prototype of an individual concept can generate a whole new set of similarity and dissimilarity relations for several related concepts, in particular those from the same contrast set, and lead to translation difficulties and incommensurability between the communities involved. Thus, the prototype account of concept representation supports Kuhn's insight that incommensurability is a regular accompaniment of conceptual change and that incommensurability can be caused by conceptual changes of a small number of concepts.

The prototype account can also lend support to Kuhn’s idea that incommensurable paradigms can still be rationally compared. According to Barsalou, the generation of prototypes and graded structures involves interactions between two factors: the stereotype and the knowledge base. The knowledge base for a given concept is an aggregation of various information about the referents, which may or may not be articulated. For example, the knowledge base for the concept “bird” includes average values on dimensions such as size and shape, as well as correlated properties such as having feathers and laying eggs. The content of a knowledge base is relatively independent of the particular stereotype that people accept. The function of the stereotype is to activate a small fraction of information in the knowledge base and to incorporate this information into the prototype of the concept. Hence, although two persons endorse different stereotypes, it is theoretically possible that their knowledge bases for a given concept overlap and that the information to be incorporated into the prototype is activated (at least partly) within the overlapping section. The possible overlap between knowledge bases and the possible similarities between prototypes generated by different stereotypes thus provide common ground for rational comparison between rival paradigms, quite apart from the common factors already suggested by Kuhn as basis for such comparisons (Chen 1990).

8.3.3 Limits of the prototype account

A difficulty for the prototype account may also be raised against accounts that assume concepts are definable by necessary and sufficient conditions. Such accounts unacceptably limit the allowed patterns of scientific change. The revision of a conceptual structure represented by concepts analyzed in terms of prototypes or necessary and sufficient conditions is an event that must take place at a single moment in time. At one moment the necessary and sufficient conditions accepted as defining a scientific concept are one particular list, or are centered on one particular prototype; at a later moment the scientific community adopts some new and incompatible list, or a new prototype, changing the concept and hence the conceptual structure. As the replacement of any defining condition or the substitution of a new prototype changes the concept completely, it appears that the process of conceptual revision cannot be historically extended. At best the process could last as long as the active debate for the new list of necessary and sufficient conditions or the new prototype structure. This unacceptably restricts the episodes of scientific change that can be accommodated. In particular, recent historical studies show that many episodes of change in science including the one that has been used as a prototype -- the Copernican revolution -- did not show abrupt change but exhibited strong historical continuity and change by small increments (Barker and Goldstein 1988; Barker 1993; Barker 1996). Neither the necessary-and-sufficient condition account nor the prototype account seem capable of accommodating incremental change as a possible pattern for scientific revolutions.

8.4 CONCEPTS, TAXONOMIES AND FRAMES

In this section we introduce the dynamic frame representation of concepts developed by cognitive psychologists to capture additional complexities of conceptual systems revealed by experimental studies and prefigured in Kuhn's theory of concepts. In Kuhn's mature work the most important conceptual systems are kind hierarchies or taxonomies. Taxonomies are easily represented by means of frames, but other types of conceptual system may also be represented. In the present section we use frames to examine a realistic example of taxonomic change from the history of ornithology during the Darwinian revolution. We show both that Kuhn's expectations for the dynamics of taxonomic change are confirmed in detail by this historical case, and that the changes may be rationally appraised. In the next section we apply the same techniques to extend Kuhn's original account of anomalies and to understand several aspects of the Copernican revolution.

8.4.1 Representing concepts and taxonomies by frames

A frame is a set of multivalued attributes integrated by structural connections. (Barsalou 1992; Barsalou and Hale 1993).[10] Figure 8.1 is a partial frame representation of the concept "bird." The frame divides features into two groups, attributes and values. All exemplars of bird share the

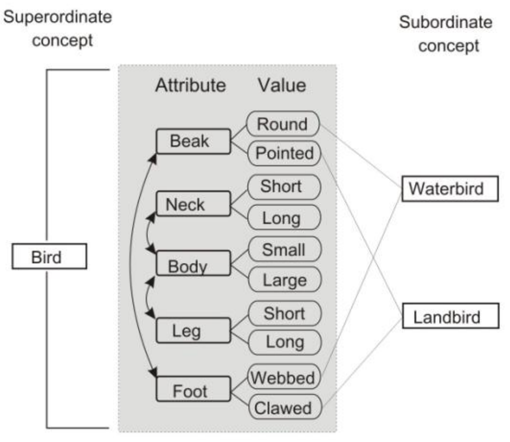

Figure 8.1 A partial frame of *bird*

properties in the attribute list such as “beak,” “neck,” “body,” “leg” and “foot.” Properties in the value list and the nodes representing superordinate concepts that lead to them are said to be “activated” (by analogy with the selective activation of nodes in a neural network) when a particular subset is chosen to represent a specific subordinate concept. For convenience and clarity, particular subordinate concepts (“water-bird” and “land-bird”) are indicated in Figure 8.1 by the lines connecting the activated value nodes to additional nodes at the extreme right; however, each subordinate concept can also be understood as a unique pattern of activation for the attribute and value nodes. Each pattern of selection constitutes the prototype of a subordinate concept; for example, a typical waterfowl is a fowl whose values for “beak,” “leg,” and “foot” are restricted to “round,” “short” and “webbed.”

The frame representation embodies two important kinds of intraconceptual relation. First, the frame captures hierarchical relations between features. Contrary to the conventional assumption that all features within a concept are structurally equal, the frame representation divides features into two different levels. Some are attributes, such as “beak” and “foot,” and the rest are values. A value is always attached to a particular attribute and functions as an instance of the attribute. Consequently, not all features within the superordinate concept are functionally equal: only attributes can be used as classification standards.

The second kind of intraconceptual relation represented in frames appears as what might be called a horizontal relation between nodes in the frame diagram. Kuhn sometimes calls this kind of connection the “legislative content” of a concept (1977, pp. 258-260). Elaborating Kuhn’s discussion, Hoyningen-Huene calls it "knowledge of regularities" (1993, pp. 13-117). There are connections between nodes at the level of attributes (structural invariants): an instance of "neck" is always physically attached to an instance of "body," and an instance of "leg" is always physically attached to an instance of "body," but an instance of "leg" is never physically attached to an instance of "neck." The suggestion, made about a real, non-defective bird, that "Here is a bird with legs that attach to its neck" would usually be treated as evidence that the speaker did not understand the concept "bird." The claim is not false but nonsensical. The unusual status of claims like "There are no birds with legs that attach to their necks" is the equivalent, in Kuhn's theory of concepts, to Kant's synthetic a priori (Kuhn 1974/1977, p. 312; Kuhn 1991, p. 12). Learning a concept like "bird" involves learning that this kind of constraint exists between its attributes.

There are also constraints that produce systematic variability in values: if the value of "foot" is "webbed," then the value of "beak" is more likely to be "round," or if the value of "foot" is "unwebbed," then the value of "beak" is more likely to be "pointed." These patterns may be understood as physical constraints imposed by nature - webbed feet and round beaks are adapted to the environment in which water birds live, but would be a hindrance on land. Because of these constraint relations, the attributes "beak" and "foot" must be used together as a cluster in classification.

A frame like Figure 8.1 may be used to represent the taxonomy of birds. It indicates that there is an inclusive relation between the superordinate concept "bird" and the subordinate concepts "water-bird" and "land-bird," and it also indicates the contrastive relations among concepts within the same subordinate group, because "water-bird" and "land-bird" should never be applied to the same object. It is acceptable to call a water-bird a bird because the concept of the former is subordinated to the concept of the latter in the frame, but not to call it a land-bird. In other words, concepts belonging to the same subordinate group cannot overlap in their referents, and so no object is both a water-bird and a land-bird. This is Kuhn's no-overlap principle for kind terms (Kuhn 1991, p. 4). In the frame representation, both inclusive and contrastive relations are embedded in the internal structure of the superordinate concept. The inclusive relation derives from the attribute list: all subordinate concepts belong to the superordinate one because they all share the properties of the attributes. The contrastive relations derive from the pattern of the activated values: two subordinate concepts contrast if they have different values in the same attribute.

The frame representation also displays the cognitive mechanisms behind the classification process. The frame of a superordinate concept directly determines the possible concepts at the subordinate level. For example, since the frame of "bird" in Figure 8.1 has five attributes and each of them has two possible values, there are 32 possible property combinations (2×2×2×2×2) and thereby 32 possible concepts at the subordinate level. But due to the constraints between the value sets, some of these property combinations are conceptually impossible. If this frame is adopted, then there are no instances of "bird" with "round beak" and "clawed foot," or with "pointed beak" and "webbed foot." Some other combinations are not found in nature. The results are only two property combinations ("round beak" with "webbed foot" and "pointed beak" with "clawed foot"), which form two subordinate concepts - "water-bird" and "land-bird." In this way, the frame specifies classification standards: birds are classified according to their beak and foot.

Originally, our use of the concept "bird" as an example was motivated by Kuhn's story about a child learning the differences between swans, geese and ducks to introduce this theory of concepts (Section 2 above). While investigating the connections between Kuhn's theory and work in cognitive science, the present authors devised some examples of taxonomic changes that fitted the cognitive analysis (Chen, *et al.* 1998). Later we were surprised to find that the hypothetical examples mirrored the development of ornithological taxonomy during the Darwinian revolution. In other words, our cognitive analysis successfully "predicted" the historical facts. A detailed examination of the sequence of historical changes that occurred in ornithology during the nineteenth century both confirms Kuhn's expectations about the mechanism of conceptual change when one taxonomy replaces another, and allows us to refute the charge that such changes are not amenable to rational comparison.[11]

8.4.2 A frame-based interpretation of taxonomic change

In the seventeenth century when the first ornithological taxonomy was developed, birds were simply divided into two classes, "water-bird" and "land-bird," according to their beak shape and foot structure (Ray 1678). Typical examples of "water-bird" were those with a round beak and webbed feet like ducks or geese, and typical examples of "land-bird" were those with a pointed beak and clawed feet like chickens or quail. By the early 19th century, however, many newly found birds could not be fitted into the dichotomous system. For example, a noisy South American bird called a screamer was found to have webbed feet like a duck but a pointed beak like a chicken.

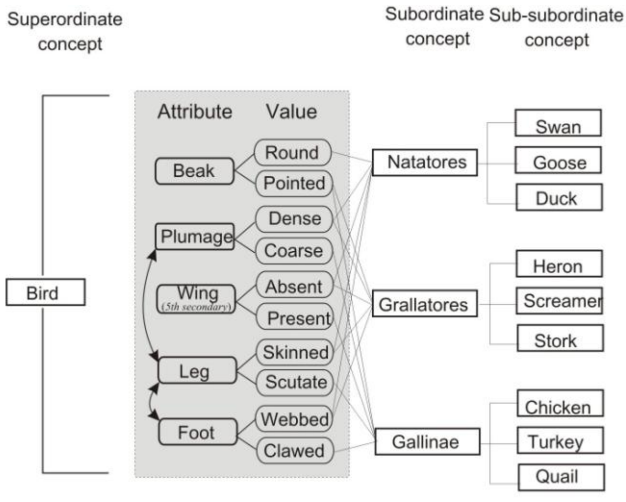

Figure 8.2 A frame representation of the Sundevall taxonomy (only three related subordinate concepts are listed)

To accommodate such anomalies a popular taxonomy proposed by Sundevall in the 1830s (Figure 8.2) adopted more attributes, including “beak shape,” “plumage pattern,” “wing-feather arrangement,” “leg form” and “foot structure,” as classification standards (Sundevall 1889). The five attributes generate more possible property combinations, and thereby more possible concepts. The Sundevall taxonomy was more flexible than the old dichotomous system, and was able to accommodate birds like the screamer that were anomalies in the old system. Because “beak” and “foot” are no long related in the Sundevall system, it becomes possible to have a property combination that includes both “pointed beak” and “webbed feet,” the key features of screamers. In this way, Sundevall eliminated the anomaly by putting “screamer” under a new category “grallatores,” independent of “water-bird” and “land-bird.”

The Darwinian revolution caused radical changes in bird classification. Influenced by Darwin’s beliefs that species change over time and therefore affinity among species must be founded on their common origin, ornithologists realized that many features used as classification standards in pre-Darwinian taxonomies were irrelevant, and they began to search for features that could display the evolutionary origin of birds. In a popular post-Darwinian taxonomy proposed by Gadow in 1893 (Figure 8.3), a different set of attributes were adopted, which included “palatal structure,” “pelvic musculature form,” “tendon type,” “intestinal convolution type” and “wing-feather arrangement” (Gadow 1892, pp. 230-256).

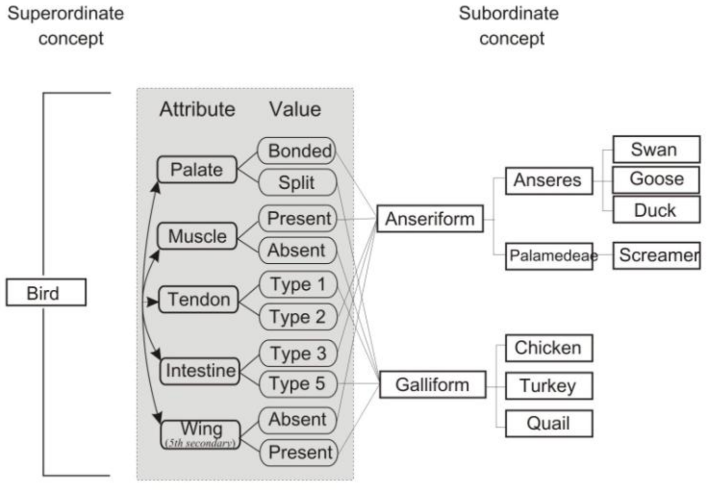

Figure 8.3 A frame representation of the Gadow taxonomy (only two related subordinate concepts are listed)

Embedded in the Gadow taxonomy is a whole new concept of "bird." The strong intraconceptual relations among all attributes reflect the assumption that similarities in these anatomical features reveal a common origin and therefore the values of these attributes ought to be correlated. The strong constraints among the attributes significantly reduce the number of the possible property combinations. For example, the combination "bonded palate" and "presented fifth secondary in the wings" exemplified by screamers becomes impossible, and Sundevall's category "grallatores"with its subconcept "screamer" cannot be included in the contrast set at the subordinate level. At the same time, the similarities between waterfowl and screamers in skull character, skeleton, wing pattern and feather structure suggested that they should be put under the same covering concept. Consequently, Gadow introduced a new subordinate concept "anseriform" to denote both waterfowl and screamers.

The frame representation shows why the pre- and the post-Darwinian taxonomies were incommensurable and confirms Kuhn's account of how incommensurability arises. Due to addition, deletion and rearrangement of kind terms, a holistic redistribution of referents occurred. Because of the referent redistribution, many terms in the new taxonomy could not be translated to the old ones, nor the other way around. Consequently, it becomes possible but not inevitable that communication between followers of the two systems will be impeded. For example, the followers of the Sundevall taxonomy might regard Gadow's category "anseriform" as confusing because they could not find an equivalent term without violating the no-overlap principle. The referents of Gadow's "anseriform" overlap those of Sundevall's "natatores" - the former includes the latter as a subset, but they are not in species-genus relations. The followers of the Gadow taxonomy, on the other hand, might regard Sundevall's "grallatores" as incomprehensible because of its overlap with "anseriform." But do these difficulties prevent rational comparison of the two taxonomies?

8.4.3 Cognitive platforms for rational comparison of incommensurable taxonomies

The pre- and the post-Darwinian taxonomies made different predictions of similarity relations. The former put "screamer" and the equivalent of "water-bird" under two contrastive covering terms and emphasized their dissimilarity, while the latter put them under the same covering term and emphasized their similarity. But observations of similarity or dissimilarity could not be used directly to test these two rival taxonomies. In a frame representation, similarity between two concepts is described in terms of the matches in the values of relevant attributes. But what should be counted as relevant attributes? Given that the taxonomic change occurred during the Darwinian revolution, ornithologists from either side shared very little in their understanding of their common objects of study. If they selected different attribute lists, would they also make incompatible judgements regarding whether an observation of similarity was relevant?

At first glance, the attribute list embedded in the post-Darwinian taxonomy is considerably different from the one in the pre-Darwinian taxonomy. But it is important to note that these two lists of attributes are compatible: none of the attributes listed in one taxonomy overlaps those in the other. A closer examination of these attributes further shows that the two lists of attributes are similar - all of them are anatomical parts of birds.[12]

The different but compatible lists of attributes embedded in the pre-Darwinian and post-Darwinian taxonomies of birds provided a common platform for rational comparison. Because the attribute lists were compatible, people from both sides could agree with each other on what attributes should be counted as relevant in judgments of similarity. When observations showed more and more similarities between screamers and water-fowl in skull character, skeleton, wing pattern, muscular system and digestive system, supporters of the pre-Darwinian taxonomy had to agree that all these similarities were relevant and accept them as legitimate evidence for testing their taxonomy. When observations of the similarities between screamers and water-birds became overwhelming, they had no choice but to admit that their taxonomy was in trouble.

Historical evidence indicates that the two rival taxonomies were indeed compared and evaluated in a rational manner. Although there were debates regarding the merits of the two rival systems, criticisms from either side were mainly based upon observations of similarity and dissimilarity relations between birds. The main objection to the pre-Darwinian taxonomy was, for example, that it grouped many dissimilar birds together (Newton 1893). Due to the compelling evidence regarding similarity and dissimilarity relations, the community quickly formed a consensus. Before the end of the nineteenth century, the Gadow taxonomy was accepted by the ornithological community (Sibley and Ahlquist 1990).

By providing a representation of the internal structure of concepts, a frame analysis shows that attribute lists embedded in two incommensurable taxonomies can remain compatible. This compatibility provides a cognitive platform for rational comparison between rival taxonomies. In this way, cognitive studies once again support Kuhn's claim that incommensurability does not necessarily entail relativism.

8.5 THE COGNITIVE STRUCTURE OF SCIENTIFIC REVOLUTIONS

8.5.1 Anomalies and the cognitive structure of revolutions

In *Structure* Kuhn claimed to have described, in a preliminary way, a pattern of development that could be found throughout science and throughout science's history. He used historical examples ranging from ancient astronomy and optics to physics in the twentieth century. But from the viewpoint of the historian, it is dramatically implausible to suggest that the usual factors considered in an historical explanation were sufficiently constant over all the periods considered by Kuhn to yield similar structures in each one. Between the ancient period and the twentieth century, the institutional structure of science, its relations to the wider culture, and the education, social class and career paths of scientists themselves changed not once but several times. Despite his insistence that the scientific community is the main actor in his account, Kuhn was adamant that such factors played little role in the intellectual changes that were his primary concern.

Rejecting the usual historical factors, a second possibility to justify the appearance of similar structures in different disciplines and different periods might be a logical reconstruction of the kind popular in the twentieth century philosophy of science. Practitioners of this view, believing that logic stood outside history, imagined that it furnished a basis for universal claims about the structure all scientific explanations, for example. However, Kuhn criticized logic-based philosophy of science as historically inadequate, and largely avoided using its tools or categories (Kuhn 1977, p. 285 and esp. Kuhn 1991).

Should Kuhn's work be seen as no more than an historical generalization based on a large range of sources? Kuhn himself would probably have defended the generality of his results as a consequence of his theory of concepts, although this only pushes the question back one step. For Kuhn, the theory of concepts is conditioned by his examination of a wide range of historical cases, but strongly influenced by the philosophical ideas of Kant and Wittgenstein. In the end Kuhn would probably have said that his theory of concepts was *a priori* (Kuhn 1979, p. 418f., Baltas, *et al.* 1997, p. 154).

The results we have reviewed in psychology and cognitive science place us in a position to offer a different answer. We wish to suggest that a more plausible explanation for both the adequacy and the generality of Kuhn's account is that it builds upon cognitive structures which have now been demonstrated by psychologists and cognitive scientists to be universal features of human intellectual activity.

A central contrast in Kuhn's original work is the division between normal and revolutionary science. We may now understand this division as the distinction between research conducted in terms of an existing conceptual structure without changing that structure, and research proceeding by modifying an existing conceptual structure (Kuhn 1983a, p. 683, Kuhn 1983b, p. 713). In principle, we should not see this division as corresponding to a linear sequence of historical changes with normal science succeeded by revolutionary science succeeded by normal science, indefinitely. Both patterns of research may coexist. However, Kuhn's later work suggests reasons for the conservative nature of normal science, and the relative infrequency of the changes in conceptual structure that we recognize as major revolutions.

As emphasized in our initial discussion of family resemblance concepts, the success of a community in classifying available instances of the objects that interest them is no guarantee that all members of the community employ the same features of those objects in arriving a classification (Andersen, *et al.*1996, p. 356) . Expressing this point in terms of a frame representation, it is always possible that different members of the same community select differing attributes, and values of those attributes, in classifying objects. This divergence may only become apparent when an anomalous object appears – a classical Kuhnian anomaly. Such an object, falling between the categories in a single contrast set, may polarize a community into those who believe it can, and those who believe it cannot, be accommodated within the existing taxonomy. The nineteenth century discovery of the South American bird called a screamer, discussed in the previous section, may be a good historical example of this phenomenon. Similar dynamics appear in the discovery of nuclear fission (Andersen 1996). However, as our earlier discussion noted, and we should not attribute taxonomic changes like those in ornithology during the nineteenth century to single anomalies, or expect them to occur at a single moment. In this case, accommodating new discoveries like the screamer led to the abandonment of an established taxonomy and the introduction of a new and incommensurable one. This episode embodies almost all the features called for in Kuhn's original account of scientific change: the old paradigm (taxonomy) generates an anomaly which can only be resolved by replacing it. One of the main assets of the new taxonomy is that it can resolve the problems that led its predecessor to crisis – it can answer the question "Is the screamer a land-bird or water-bird?". The theory of concepts we have described provides the resources for understanding both the breakdown of consensus in the scientific community created by an anomaly of this type, and the means by which it is resolved.

8.5.2 Revolution without empirical anomalies

A second and more problematic case of scientific change may be understood using the same resources. Copernicus's innovations in astronomy were not stimulated by an anomaly that violated the contrast classes for astronomical objects available in the sixteenth century. Rather, his main announced objection to Ptolemaic astronomy was its use of the mathematical device called the equant point. The Western astronomical tradition had long accepted that all celestial motions were combinations of circles traversed at constant speed. In principle, any celestial motion should therefore have three attributes: "center," "radius" and "speed of rotation" (Figure 8.4a).[13] In the simplest case, we assume that a single point serves both as the geometrical center and the center of rotation; the geometrical center of a celestial circle serves both as the initial point of its radius, and as the point from which the angular motion of an object moving around the circle is measured. Probably because he was unable to accommodate both the direction and the duration of retrogressions using this simple conceptual structure, Claudius Ptolemy, in his main astronomical

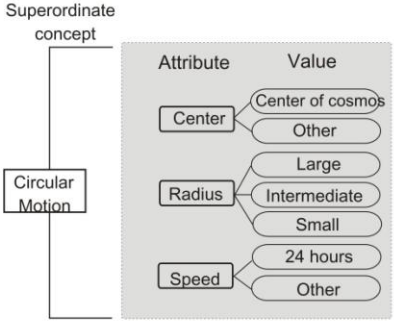

Figure 8.4a Partial frame for circular motion

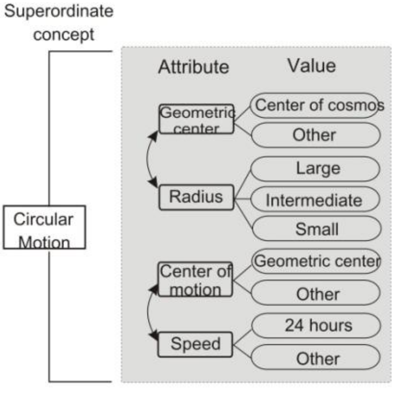

Figure 8.4b Partial frame for circular motion modified to accommodate Ptolemys equant device

work, both separated the observer from the geometrical center of the major celestial circle carrying a planet, and, more radically, separated the center of rotation from the geometrical center (Evans 1998). The removal of the observer (that is the earth) from the geometrical center made the circle eccentric. Ptolemy located the center of rotation at the same distance from the geometrical center as the observer but diametrically opposite, and called this the equant point. In all his models except those for the sun and moon, Ptolemy employed this unusual conceptual structure.

Although astronomers in the Ptolemaic tradition employed the equant device when making calculations, it was a long-standing source of dissatisfaction with Ptolemy's models. By means of frame diagrams the problem may be posed as follows: how are we to modify Figure 8.4a to accommodate the equant, and are we obliged to make similar modifications in the frames for other rotating circles? The simplest modification would seem to be to add a new attribute at the same level as the three already included.

However, in the same sense that we cannot specify a radius without specifying a geometrical center, it now appears that we cannot specify the rotation of a circle without introducing a center of rotation that may differ from the geometrical center. So we also need to introduce constraints showing that these pairs of nodes can only be activated together or not at all (Figure 8.4b). The discrepancy in nodes and constraints between Figure 8.4a and Figure 8.4b is of exactly the same kind as the discrepancy between nodes in incommensurable taxonomies. Historically, astronomers expressed a strong preference for conceptual structure 4a, despite the use of the equant as a calculating device. Copernicus's success in constructing planetary models which avoided this device – at least overtly – was greeted with acclaim by his contemporaries. What this case teaches us is that conceptual structures may be objectionable – and hence motivate change – for other reasons than their adequacy in coping with empirical anomalies. This analysis also shows that although Kuhn's original exposition of the Copernican revolution could not be assimilated to his general model of scientific change, if we examine the conceptual structures represented by the different positions in astronomy during the Copernican revolution, the same cognitively based theories which supported Kuhn's original account of anomaly-induced change can also be used to understand the mechanisms at work here.

The theory of concepts and taxonomic structures developed by Kuhn and here presented through the frame account also provides a means for locating incommensurability at particular points within a conceptual structure, and appraising its severity (Figure 8.5). Consider a partial frame representation of the main positions in astronomy before and after Copernicus, ignoring for the moment the complications introduced by the equant, and considering only the major motion of a planet, its so-called proper motion against the background of fixed stars (Barker 2001). The differences between the two main schools in astronomy before Copernicus come down to different choices for the values a single attribute of the celestial circle corresponding to this motion. Averroists insisted that all celestial circles must take the earth as their center (Figure 8.5a). Ptolemaic astronomers allowed the circle for the proper motion to have a different center, which for some planets was quite distant from the center of the earth (Figure 8.5b).

It is surprising to discover that Copernicus's planetary models can be accommodated by the same conceptual structure as Ptolemaic astronomy (Figure 8.5c). Although there are minor differences in numerical values for the attributes "radius" and "speed" (Copernicus generally uses Ptolemy's distances for example), these differences can be accommodated without

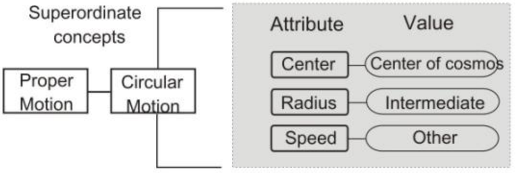

Figure 8.5a Partial frame for Averroist theory of proper motion

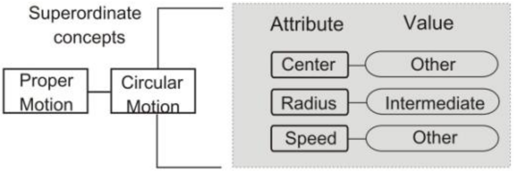

Figure 8.5b Partial frame for Ptolemiac theory of proper motion

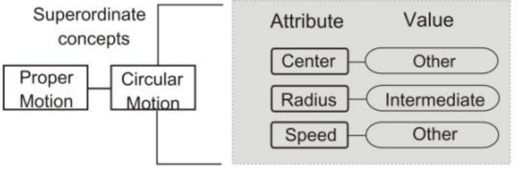

Figure 8.5c Partial frame for Copernican theory of proper motion

introducing new attributes or new ranges of values. The topography of Copernicus's frame is identical to the Ptolemiac one. It has the same branch structure, and the same nodes linked in the same clusters. From the viewpoint of sixteenth-century astronomers, Copernicus's location of the center of a planet's proper motion at the mean sun was just the choice of a new eccentric center for the circle representing proper motion. But Ptolemaic astronomers were already using such points, and consequently saw Copernicus not as a threat to Ptolemy, but as a potential ally in the dispute with the Averroists (Lattis 1994; Barker 1999, 2001).

If we compare these three conceptual structures with the corresponding portions of the frame for Kepler's astronomical theory, a major incommensurability is immediately apparent. Not only have a new set of attributes and values been introduced, but the superordinate node corresponding to "circular motion" in the earlier frame diagrams has now been replaced with the node for a new concept – "orbit" (Barker 2001). It is interesting to note that this revision of nodes occurred in a conservative way – the innovations Kepler introduces fit into the existing conceptual structure and replace existing nodes conserving the original branch pattern (Barker and Goldstein 2001). However it is clear that Kepler's work introduced a radical

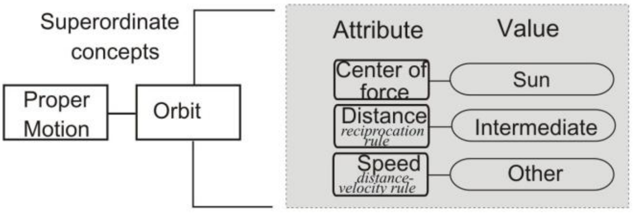

Figure 8.5d Partial frame for Keplers 1609 theory of proper motion

revision in concepts. Superimposing the frame diagrams for Kepler's system and any of the earlier ones shows that reading from the left we immediately encounter conflicting choices for a series of nodes. The extent to which these changes reach into the superordinate nodes may be used as an estimate of the severity of the incommensurability introduced here (Barker 2001). Using this criterion to compare Figures 8.5c and 8.5d, we see that Kepler's theory of proper motion is incommensurable with Copernicus's to the same degree it is with Ptolemy's. This is initially surprising, until we recall that it was Kepler's version of Copernican astronomy, not the model proposed by Copernicus himself, which ultimately displaced the Ptolemaic system.

The examples we have considered show that conceptual change may be an incremental process that is historically extended. Given enough incremental change, the revised conceptual structure may be so different from an earlier historical example that an historian of science looking at two periods fifty years or a century apart may mistakenly conclude that the transition from one structure to another was discontinuous (Chen and Barker 2000). Using a tool like the frame model not only provides a means of identifying the small incremental changes that actually linked the two structures, but by locating the positions of the changes it also directs our attention to the historical arguments used to justify them. For example, Galileo's discovery of the moons of Jupiter was important to both Ptolemaic astronomers and Copernican astronomers because it showed that four newly discovered objects moved in circles around a center that was clearly not the center of the earth. In conceptual terms it showed that the Averroists' insistence on their preferred value for the "center" attribute, and hence the frame in Figure 8.5a, was flatly untenable.

8.6 CONCLUSION

According to the received view of Kuhn's work, incommensurability between rival conceptual systems is either total, or risks being total; it prevents meaningful communication between supporters of different systems, and it prevents rational comparison of competing incommensurable systems. Although Kuhn himself repeatedly rejected these interpretations of his work, they continue to dominate the philosophical literature (Curd and Cover 1998). At the same time, philosophy of science has largely turned away from historical studies. One reason for this was the intractability of systems that attempted to do the same historical work as Kuhn without the same imagined philosophical liabilities (Lakatos 1977; Laudan, *et al.* 1986). But a second and more important reason may have been an aggressive campaign mounted by sociologists of science to co-opt historical studies of science (Bloor 1976; Shapin 1982). Although many of the methodological criticisms levelled at historical-orientation philosophy of science by sociologists were accurate, their own program had two major drawbacks: it denied the centrality of the cognitive content of science in explaining scientific change, and it generally included a parallel attack on scientific realism. During the last two decades of Kuhn's life, philosophers of science withdrew from historical work and devoted a disproportionate amount of intellectual effort to defenses of realism.

Perhaps the cognitive rereading of Kuhn will finally deflate some of the myths about his work. On the basis of the cognitive reconstruction of Kuhn we have offered, it is apparent that total failure of communication between opposing groups with incommensurable conceptual structures is not to be expected. Quite the reverse, the analysis shows a wide range of factors that support mutual intelligibility and rational appraisal of competing positions. But the work presented here has a far more important outcome than correcting misreadings of Kuhn. Kuhn's later work, as augmented by results from cognitive theories of concepts, constitutes a complete answer to the sociological critique of philosophy of science.

The analysis we have presented by means of the frame model satisfies all the desiderata that motivated the Strong Programme in the sociology of knowledge. But it does this while restoring the centrality of cognitive content in our philosophical picture of science, and providing empirically licensed access to the conceptual structures employed by scientists today and in history. To review briefly, the Strong Programme required that any account of science be first, causal, that is empirical; second, reflexive; third, symmetrical, and fourth, impartial. When represented by means of dynamic frames, Kuhn's theory of concepts ceases to be *a priori* and becomes empirical. It is evidently reflexive: one of the simplest ways to delineate the differences between the prototype model of concepts and the frame model would be to construct frames for the concepts "prototype" and "frame."[14] As for symmetry and impartiality, frame analysis applies equally to accepted and rejected, successful and unsuccessful theories, and its application is independent of the truth or falsity of the theory under examination. The frame model provides a method of representing conceptual structures; using it corresponds to the analysis of meaning, not the evaluation of truth bearing structures, which is what philosophers of science have generally taken theories to be.

Establishing the positive links we have described between Kuhn's later philosophy of science and empirical investigations of concepts therefore opens a whole new avenue of enquiry into issues in the philosophy of science first examined by Kuhn. This enquiry may well reach results that are unexpected and that Kuhn himself did not envisage. Nor would we wish to give the impression that the frame model is the last word in the theory of concepts. Like any empirical theory it is susceptible to improvement or replacement. It remains true, however, that any empirical account of concepts capable of accommodating experimental data gathered from the time of Rosch's original work to the present will also support the account of concepts developed by Kuhn in his mature work, and, we maintain, will lead by equivalent reasoning to the results we have documented based on Kuhn's ideas and the frame model. Kuhn's lasting contribution to the philosophy of science may well be his least popular: the concept of incommensurability. But ironically the theory of concepts developed as he refined this idea now provides a means to restore the central importance of cognitive content in philosophy of science and a means to approach the history of scientific change that places the subject on a secure empirical footing.

Notes:

Peter Barker gratefully acknowledges the support of the University of Oklahoma sabbatical leave program, the Danish Institute for Advanced Studies in the Humanities, and Denmark's Nationalbank, for portions of this work. Parts of section 4 were previously published in Chen (2000), copyright 2001 by the Philosophy of Science Association.

1. Kuhn himself describes the profound effect of reading Kant while a student at Harvard (Baltas, *et al.* 2000, p. 264). His debt to Wittgenstein is apparent in *Structure,* the final stages of which were begun only five years after the appearance of the *Philosophical Investigations* (1953), and at the height of interest in Wittgenstein's later work. Kuhn's knowledge of that book and its author may have been mediated by Stanley Cavell while they were both at Berkeley (Kuhn 1962/1996, p. xiii). At the same time he was in contact with Paul K. Feyerabend, who wrote one of the first and most influential reviews of the *Investigations*. However, while Feyerabend remained an outside observer, Cavell was one of only a handful of philosophers who adopted and actively employed the methods of

Wittgenstein's later work, as Kuhn would go on to do.

2. The procedure by which science students are supposed to model novel problems on the exemplary problems is analogous to the procedure by which Latin students learn to recite *amo, amas*, ..., and then conjugate similar verbs by matching the same endings to new stems. Kuhn adopted the expression for such standard examples in language teaching, "paradigm," and simply extended it to cover standard examples in science teaching.
3. See Andersen, Barker and Chen (1996), Barker (1986), and Andersen (2000b) for accounts of the relation between Kuhn and Wittgenstein's accounts of family resemblance.
4. In his published work Kuhn never referred to the literature on concept acquisition, but drew on everyday experience. For the similarity between Kuhn's account and the account developed by cognitive psychologists on the basis of extensive experiments on concept learning and categorization, see e.g. Andersen, Barker and Chen (1996) and Nersessian (1998).
5. The only example of the acquisition of scientific concepts which Kuhn spelled out in some detail is his analysis of how students learn the concepts force, mass and weight, see Kuhn (1989, pp. 15-21) and Kuhn (1990, pp. 301-308).
6. Kuhn's restriction of dissimilarity to instances of concepts forming contrast sets can also be found in other fields, such as the cognitive psychology, e.g. Rosch (1987, p. 157), or ethnographic semantics and cognitive anthropology, e.g. Conklin (1969) and Kay (1971).
7. On this point, Kuhn explicitly claimed to have moved beyond Wittgenstein: "Wittgenstein ... says almost nothing about the sort of world necessary to support the naming procedure he outlines" (Kuhn 1970a, p. 197, fn. 14).
8. Kuhn's concept of kind went beyond the one defined by the traditional theory of natural kinds, and Kuhn also disagreed with Hacking, who advocated a notion of "scientific kind" (Hacking 1993, p. 290). Kuhn suggested that kinds are "substances" that "trace a lifeline through space and time" so that they can be reidentified by our "categorizing module" (Kuhn 1993, p. 315; 1990, p. 5).
9. This is the so-called non-overlap principle for kind terms, which plays a very important role in Kuhn's new incommensurability thesis. For more analysis of the non-overlap principle and its relations to Kuhn's latest incommensurability thesis, see Chen (1997).
10. Frames were introduced by Minsky in the 1970s to represent knowledge as part of an unsuccessful program to develop artificial intelligence Minsky (1975). Minsky's frames originated from Bartlett's notion of a schema. See Brewer (2000).
11. Recent cognitive studies offer further evidence to justify the use of frames to represent concepts by revealing the connections between concepts and neural structures; see Barsalou (1999), Barsalou, et al. (1999), and Chen (2001).
12. In the light of cognitive studies, there is reason to believe that such a preference was not accidental, but reflects a general feature of human cognition (Rosch, *et al.* 1976; Tversky and Hemenway 1984).

13. For an explanation of the values displayed in the frame, see Barker, 2001. For a detailed discussion of the equant problem, see Barker (unpublished).
14. We leave this as an exercise for the reader.

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