Kuhn's theory of scientific revolutions and cognitive psychology

XIANG CHEN, HANNE ANDERSEN & PETER BARKER [1]

ABSTRACT *In a previous article we have shown that Kuhn's theory of concepts is independently supported by recent research in cognitive psychology. In this paper we propose a cognitive re-reading of Kuhn's cyclical model of scientific revolutions: all of the important features of the model may now be seen as consequences of a more fundamental account of the nature of concepts and their dynamics. We begin by examining incommensurability, the central theme of Kuhn's theory of scientific revolutions, according to two different cognitive models of concept representation. We provide new support for Kuhn's mature views that incommensurability can be caused by changes in only a few concepts, that even incommensurable conceptual systems can be rationally compared, and that scientific change of the most radical sort—the type labeled revolutionary in earlier studies—does not have to occur holistically and abruptly, but can be achieved by a historically more plausible accumulation of smaller changes. We go on to suggest that the parallel accounts of concepts found in Kuhn and in cognitive science lead to a new understanding of the nature of normal science, of the transition from normal science to crisis, and of scientific revolutions. The same account enables us to understand how scientific communities split to create groups supporting new paradigms, and to resolve various outstanding problems. In particular, we can identify the kind of change needed to create a revolution rather precisely. This new analysis also suggests reasons for the unidirectionality of scientific change.*

1. Introduction

In our previous paper (Andersen *et al.*, 1996), we have shown that the most radical features of Kuhn's theory of concepts, particularly the rejection of the traditional view that concepts can be defined by necessary and sufficient conditions, are independently supported by recent research in cognitive psychology. Our main concern in this paper is Kuhn's theory of scientific revolutions, which may be most readily understood in terms of a cyclical model (Figure 1), with elements that are no doubt familiar to a majority of our readers. This model has usually been understood as an inductive generalization based on the history of science. Recently, both philosophers of science and cognitive scientists have begun to examine its cognitive

Xiang Chen, Department of Philosophy, California Lutheran University, Thousand Oaks, CA 91360-2787, USA. Hanne Andersen, IMFUFA, University of Roskilde, DK-4000 Roskilde, Denmark. Correspondence to: Peter Barker, Department of the History of Science, University of Oklahoma, 601 Elm, Room 622, Norman, OK 73019-0315, USA.

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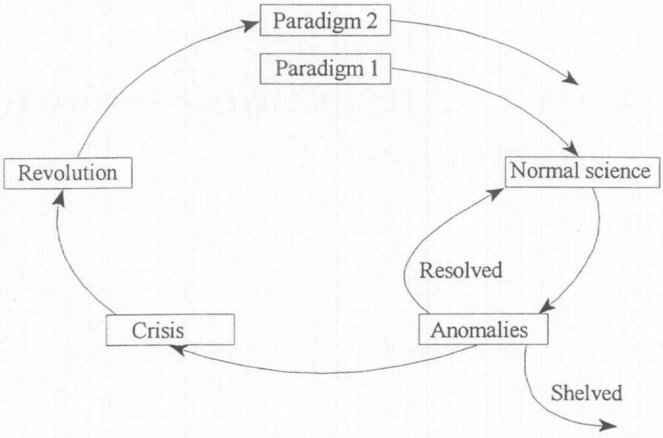

FIG. 1. Kuhn's cyclical model of scientific revolutions.

foundations (Carey, 1991; Thagard, 1992; Nersessian, 1995). In this paper, we wish to propose a radical reappraisal of Kuhn's model. Specifically, we suggest a re-reading of the model on the grounds of a particular cognitive account of human concepts—the frame model—which has been developed by cognitive psychologists over the last decade [2]. We will show that all of the important features of Kuhn's model may now be seen as consequences of this fundamental account of human concepts and its dynamics. To the extent that this model applies in the history of science it is because scientific concepts share features in common with all human conceptual systems, as revealed by cognitive psychology.

If we consider Kuhn's mature account of incommensurability from the viewpoint of cognitive science, extending the approach taken in our previous paper, we find again that research in psychology and cognitive science clarifies the cognitive phenomenon of incommensurability and lends additional support to Kuhn's position. We will elaborate the notion of incommensurability, the central theme of Kuhn's theory of scientific revolutions, according to two different cognitive models of concept representation. This will allow us to support Kuhn's later view that incommensurability can be caused by changes in only a few concepts, that even incommensurable conceptual systems can be rationally compared, and that scientific change of the most radical sort—the type labeled revolutionary in earlier studies—does not have to occur holistically and abruptly, but can be achieved by a historically more plausible accumulation of smaller changes.

We will suggest that Kuhn's theory of scientific revolutions must be understood on the basis of his theory of concepts. We will go on to suggest that the parallel accounts of concepts found in Kuhn and in cognitive science lead to a new understanding of the nature of normal science, of the transition from normal science to crisis, and of scientific revolutions. Normal science may now be recognized, not as a state of total homogeneity in beliefs or conceptual structure within a given scientific community, but rather as a period in which divergences in the application of concepts are latent rather than overt. During a crisis phase, these divergences become manifest, through the appearance of a crisis-causing anomaly. The anomaly itself may be understood, on this representation, as an object or situation that creates divergent attempts to accommodate it using the community's existing conceptual resources. Whether a crisis leads to a revolution, or back to normal science, will depend on the extent to which the community can accommodate the anomaly without revision of fundamental conceptual structures. The new account of concepts introduced by Kuhn, and parallel accounts in cognitive science such as frame theory, enable us to understand how scientific communities split to create groups supporting new paradigms, and to understand this process in sufficient detail to resolve various outstanding problems. In particular, we can identify the kind of change needed to create a revolution rather precisely. This new analysis also suggests reasons for the unidirectionality of scientific change.

2. The development of Kuhn's concept of incommensurability

The most important concept in Kuhn's account of science omitted in Figure 1 is the concept of incommensurability. For many people this is the central notion of Kuhn's theory of scientific revolutions, and defines the nature of the conceptual divide between the stages separated by revolutions (Hoyningen-Huene, 1993; Sankey, 1994; Hoyningen-Huene *et al.*, 1996; Chen, 1997). In *The Structure of Scientific Revolutions*, Kuhn suggested that the proponents of rival paradigms practiced their trades in different worlds, by formulating different problems, by adopting different standards for problem solutions, and by employing different meanings for concepts. Consequently, scientists experienced difficulties in evaluating rival paradigms, because there were few shared standards and shared concepts among them. Kuhn used gestalt shifts as an analogy to illustrate incommensurability: scientists see things in an entirely different way after a revolution, as if wearing glasses with inverting lenses (Kuhn, 1970, p. 122).

From the metaphorical description of paradigm changes as 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, that incommensurability allows rational comparisons of successive theories or paradigms and that it does not imply relativism (Kuhn, 1991, p. 3; 1989, p. 23; 1983a, p. 670; Hoyningen-Huene, 1993, ch. 6.3).

To show the possibility of rational comparison, Kuhn made several significant revisions in his later explications of incommensurability. His first revision was to drop the gestalt analogy, abandoning the perceptual interpretation as well as the implication that revolutionary changes are instantaneous. To clarify the meaning of incommensurability, he developed a metaphor based on language: during scientific revolutions, scientists experience translation difficulties when they discuss theories, concepts, or terms from a different paradigm, as if they were dealing with a foreign language. Incommensurability thus is confined to changes in the meaning of concepts, and becomes a sort of untranslatability (Kuhn, 1970, p. 198; Hoyningen-Huene, 1993, ch. 3).

Kuhn's next important revision was to narrow the scope affected by revolutions. In the early 1980s, he introduced a notion of "local incommensurability", claiming that

> [during a scientific revolution], most of the terms common to the two theories function the same way in both; their translation is simply homophonic. Only for a small subgroup of (usually interdefined) terms and for sentences containing them do problems of translatability arise. (Kuhn, 1983a, pp. 670–671)

Continuing this direction, Kuhn further limited his scope by introducing a theory of kinds. He says that

> [B]y now, however, the language metaphor seems to me far too inclusive. To the extent that I'm concerned with language and with meanings at all, ... it is with the meanings of a restricted class of terms. Roughly speaking, they are taxonomic terms or kind terms, a widespread category that includes natural kinds, artificial kinds, social kinds, and probably others. (Kuhn, 1991, p. 4) [3]

With this new understanding of incommensurability, Kuhn refined the concept of holism that has always characterized his philosophy of science. Giving up the global holism developed in the *Structure of Scientific Revolution*, Kuhn ultimately emphasized the local features of incommensurability. Instead of discussing a global entity such as a paradigm or a disciplinary matrix, he focused more narrowly on kind terms. The meaning change of kind terms, however,

> ... is an adjustment not only of criteria relevant to categorization, but also of the way in which given objects and situations are distributed among preexisting categories. Since such redistribution always involves more than one category and since those categories are interdefined, this sort of alteration is necessarily holistic. (Kuhn, 1981, p. 20)

In our previous paper we described changes of this sort as involving the reconstitution of the fundamental relations that constitute concepts for Kuhn (relations of similarity and difference), and showed how Kuhn's account could be independently supported by cognitive studies of the nature of concepts and represented by means of dynamic frames.

When the meanings of kind terms change, it may be difficult or impossible to translate kind terms between different taxonomies, and incommensurability between the conceptual structure of different scientific communities occurs as a consequence. On the other hand, because meaning change happens only in a very restricted class of terms, there always exist unchanged concepts, and possibly common problem-solving standards, that may be used as a basis for rational comparison between rival paradigms during scientific revolutions. Through the localization of incommensurability, Kuhn also 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 paper, we again find that research in psychology and cognitive science clarifies the cognitive phenomenon of incommensurability and lends additional support to Kuhn's position.

3. A feature list model of local incommensurability

According to Kuhn, incommensurability is directly caused by changes of conceptual structure. "The practice of normal science depends on the ability, acquired from exemplars, to group objects and situations into similarity sets .... One central aspect of any revolution is, then, that some of the similarity relations change" (Kuhn, 1970, 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. Thus, the meaning of "planet" changed during the revolution, and related translation difficulties or communication failures occurred.

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 science is the so-called feature-list model, which characterizes people's knowledge of a concept as a list of independent features. In our previous paper we 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. Briefly, whatever human concepts are, it is clear from modern research in psychology and cognitive science that they are not things definable by necessary and sufficient conditions.

Rather than specifying concepts by definitions, many recent feature-list accounts represent concepts by prototypes (Barsalou, 1985, 1987, 1990; Homa, 1984; Smith & Medin, 1981). A prototype is a typical or ideal 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.

The prototype account can provide a dynamic account of concept formation. According to Barsalou, for example, prototypes are constructed in the working memory of our cognitive system, but the information contained in prototypes comes from a knowledge base in long-term memory (Barsalou & Sewell, 1984, pp. 36–46; Barsalou, 1987). The knowledge base for a concept may contain a tremendous amount of information, but, very importantly, 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 cultural or theoretical backgrounds. In this way, the prototype theory illustrates the critical role of paradigms, the key 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 only as moderately good examples of "bird", while those who took a Chinese cultural perspective developed a prototype of "bird" quite similar to swans, and regarded robins as less typical (Barsalou & Sewell, 1984, pp. 15–26). This experiment shows that these two cultural perspectives generate dissimilar prototypes and hence the potential to categorize new objects in different ways [4].

The impact of cultural and theoretical stereotypes is localized, because they generate different prototypes for individual concepts. The result of these local changes, however, can be 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 our previous paper, similarity and dissimilarity relations also define the connections between a concept and the others under the same superordinate concept, that is, those from 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 due to changes in cultural or theoretical stereotype, 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". There would be significant overlap between "bird" and "mammal" and communication between community members may be jeopardized [5]. 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. As shown in the example above, this may lead to translation difficulties and incommensurability between the sub-communities involved, due to the interrelations among these concepts. These considerations show that any account of concepts incorporating elements like prototypes introduces the possibility that incommensurability will arise during conceptual change. The example just considered also shows that feature-list models of concepts using prototypes may support Kuhn's insight that incommensurability can be caused by conceptual changes of a small number of concepts in a larger group.

The feature-list model, when interpreted in the form of the prototype account, can also lend support to Kuhn's idea that incommensurable paradigms can still be rationally compared. As proposed by Barsalou, for example, the generation of prototypes and graded structures involves interactions between two factors: the stereotype and the knowledge base of the concept. The knowledge base for a given concept is an aggregation of various information about the referents, which may or may not be articulated [6]. 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 or cultural background that people accept. The function of the stereotype or cultural background 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 or have different cultural backgrounds, it is theoretically possible that their knowledge bases for a given concept overlap and that the information to be incorporated into the prototype of the concept is activated (at least partly) within the overlapping section. The possible overlap between knowledge bases and the possible similarities between prototypes generated by different or rival stereotypes thus provide common ground for rational comparison between rival paradigms, quite apart from the common factors already suggested by Kuhn as the basis for such comparisons (Chen, 1990).

4. Continuity in revolutions and the frame model

Although the feature-list model gives a promising beginning for a cognitive account of incommensurability, it is unsatisfactory in two respects.

First, the feature-list model using prototypes describes the dynamics of conceptual change through graded structures alone. Strictly speaking, however, graded structures merely describe the behavior of people ordering exemplars in categories according to their typicality (Barsalou, 1987). But there is clearly more to conceptual structure, and hence to conceptual change, than is reflected in this behavior pattern. One such element has been labeled a "conceptual core" by critics of the prototype account. Some critics have even suggested that graded structures would disappear if the information from conceptual cores is considered, and that the classical account of concepts can be saved (Armstrong *et al.*, 1983; Rey, 1985). While pessimistic about saving the classical account, we agree that the feature-list model, even augmented with prototypes, omits important elements in any conceptual structure.

Second, and more important, the feature-list model suggests only one pattern of revolutionary change in science. In common with many readings of Kuhn's early work it suggests that the pattern of conceptual change in scientific revolutions is inevitably abrupt. While changes at the level of empirical observation may be continuous (the discovery of new birds or new features of known birds), changes of taxonomy shared by a scientific community will not be. To establish these points let us briefly consider an extension of the taxonomic categories introduced in our

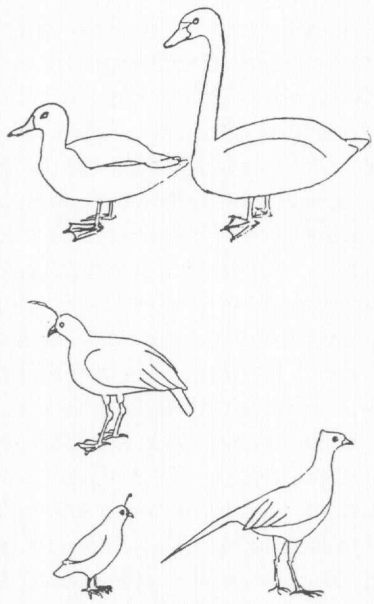

FIG. 2. Waterfowl, screamer and gamebirds.

previous paper, where following Kuhn we used waterfowl as the basis of the example.

Consider, for example, a group of people who are equipped with the usual North American conceptual structures covering the similarities and differences between waterfowl and game birds. Suppose they encounter a South American bird from the family Anhimidae, called a “screamer” (Figure 2). They will see a bird with a pointed beak but webbed feet. How should this creature be classified? According to the prototype account, an object is classified according to its similarity to the prototypes of existing classes, in terms of a list of relevant features. As shown in our previous paper, none of these features is a necessary condition for defining the concept, and no single one must be used in classification. Different people, and even the same person at different times, could activate different features as classification standards. Thus, there seem to be two possible ways of classifying the screamer. Taking the shape of the feet as the most important classification criterion makes it a waterfowl. Focussing on the shape of the beak, however, makes it a game bird. In either case, the anomaly is temporarily resolved on an individual basis, although the new bird may be a relatively poor example of either of the categories used to classify it. The appearance of different classification standards reflects a normal feature of human concepts—their flexibility (Barsalou, 1993)—and does not generate any urgent need for immediate taxonomic change.

Even when someone wants to alter the taxonomy, the prototype account, like other feature-list accounts, contains no mechanism connecting classification anomalies to taxonomic changes. To move from anomalies to taxonomic change, we may need to conjecture something along the lines of Kuhn’s earlier account of revolutionary change. On this account we would expect the taxonomic change to be preceded by a proliferation of anomalies leading to a crisis state. For example, if bird watchers found that screamers had more anomalous features, or discovered some other birds that blurred the line between waterfowl and game birds, they might develop doubts about the previous classification that puts "waterfowl" and "game bird" together in a contrast set under a superordinate category of "fowl". The accumulation of anomalies could eventually erode their faith in the whole existing taxonomy of "fowl", and cause a crisis. At some point, the community might decide to change the current taxonomy substantially, and to reconstruct an entirely new taxonomy of "fowl" reflecting the peculiar taxonomic status of screamers. However, from a historical viewpoint the conceptual shift from the old taxonomy to the new one would occur at a single moment, immediately after the hypothetical decision to adopt it had been taken in the relevant community.

Thus, according to the feature-list model, there may be continuous changes at the level of empirical observation, but changes at the level of taxonomy are discontinuous. Taxonomic changes may well occur only after an accumulation of anomalies as well as a stage of psychological crisis, but they will take the form of abrupt and instantaneous shifts. 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 & Goldstein, 1988; Barker, 1993, 1996). The feature-list model seems incapable of accommodating incremental change as a possible pattern for scientific revolutions.

To provide a possible cognitive mechanism behind taxonomic changes, and to show how continuity through incremental change may occur during revolutions, we return to the general model of concepts introduced in our previous paper: Barsalou's dynamic frames (Barsalou, 1991, 1992; Barsalou & Hale, 1993; Andersen *et al.*, 1996).

Let us briefly review the frame model, as developed by Barsalou to capture the structural aspects of human concepts, and relate it to our example using birds. Frames are co-occurring sets of multivalued attributes that are integrated by structural connections. They are not rigid—attributes in a frame are features most likely to occur across the examplars of the concept. The frame model highlights three important structural relations within concepts.

First, the frame model captures hierarchical relations between features. Contrary to the conventional assumption that all features within a concept are structurally equal, the frame model divides features into two different levels: *attributes* and *values*; the latter are instances of the former.

Second, the frame model captures several stable relations between the attributes. Because these relations hold across most exemplars of concepts, they form relatively invariant structures between the attributes, and are thus called *structural invariants*.

Third, the frame model also captures constraints that produce systematic variability in the values of the attributes. These constraints either affect a particular

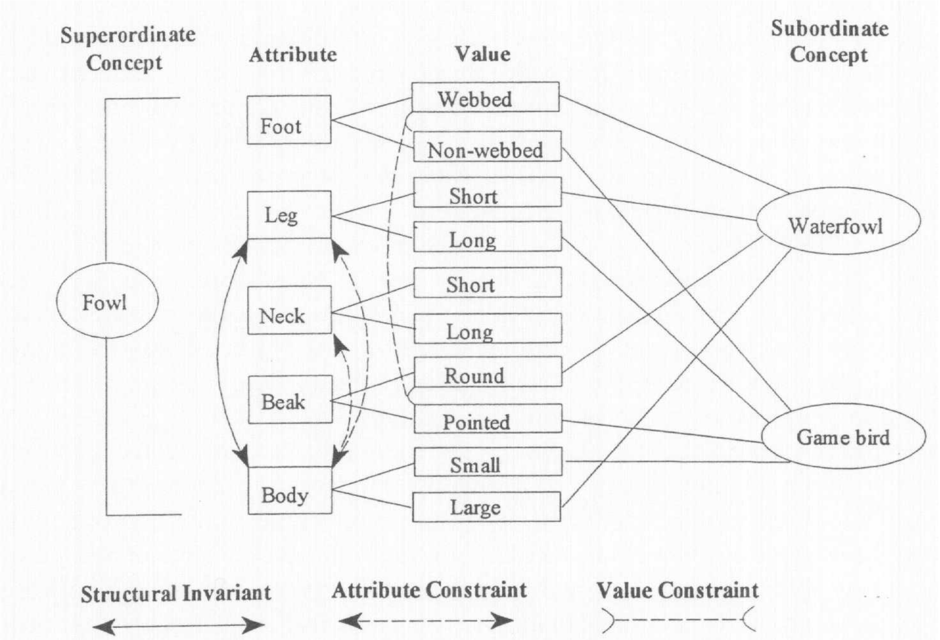

FIG. 3. A partial frame for "fowl".

pair of values locally, specifying how a particular value of an attribute is related to a particular value of another attribute (value constraint), or affect value sets globally, imposing correlations between all values of specific attributes (attribute constraint). In terms of their sources, constraints include physical restrictions demanded by nature, as well as intentional limitations initiated by human agents [7].

Figure 3 is a partial frame representation of the concept of "fowl". Features in this frame model are divided into two groups: attributes and values, and some values (such as "large" and "small") are always related to a particular attribute (such as "body"). Structural invariants exist between some of the attributes, for example, between "leg" and "body"—the relations between these two attributes reflect not only co-occurrence but physical connections (legs carry bodies). The frame also shows several attribute constraints, such as the one between leg length and body size. This is a physical constraint: a correlation must exist between these two attributes, otherwise fowl would not be able to achieve balance. For similar reasons there is also an attribute constraint between neck length and body size. The frame also has a value constraint between the values of "beak" and "foot": if the value of "foot" is "webbed", then the value of "beak" is more likely "round", or if "foot" is "non-webbed", then "beak" is more likely "pointed". This is a physical constraint 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.

Turning now to the representation of scientific change, the frame model of concepts shows that the appearance of a single anomaly can cause immediate taxonomic changes, and is therefore more flexible and wider in scope than the

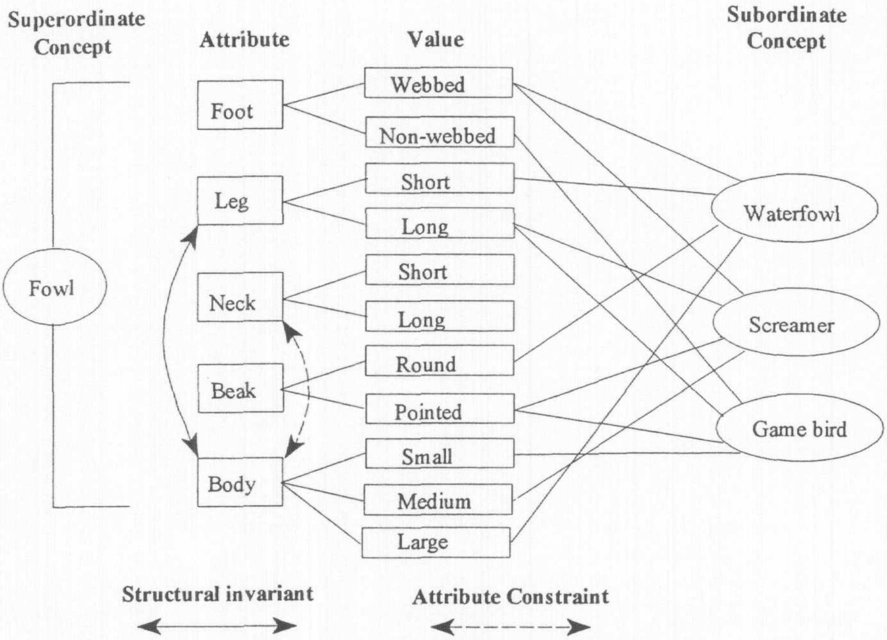

FIG. 4. A partial frame for "fowl", with modifications.

feature-list model. Because there are constraints on attributes and values in the frame model, classification standards must sometimes be used in clusters. For example, the value constraint between "foot" and "beak" in the frame of "fowl" requires that these two attributes be used together in classification. Thus, the discovery of the South American bird introduced above—the "screamer"—will immediately generate problems, because we do not know how screamers should be classified according to the cluster of standards for "foot" and "beak". This anomaly will force us to alter the frame of "fowl", because it makes a very important constraint relation between "foot" and "beak" invalid. The anomaly posed by screamers also violates the constraint between "leg" and "body", because long-legged screamers have only a medium-size body.

As we have indicated in our previous paper, the frame of a superordinate concept determines the conceptual field for its subordinate concepts. With structural invariants, attribute constraints and value constraints, a frame defines the possible value combinations, and thereby specifies the legitimate subordinate concepts. Thus, the disappearance of some constraints in the frame "fowl" makes new value combinations possible, and alters the subordinate contrast sets. For example, because now there is no constraint between "foot" and "beak" as well as between "leg" and "body", a new set of value assignments such as "webbed foot", "long leg", "pointed beak" and "medium size", becomes possible [8]. This value combination represents a new subordinate concept, "screamer", and the contrast set at the subordinate level has a new member (Figure 4).

This taxonomic change, however, can hardly be called revolutionary. With a

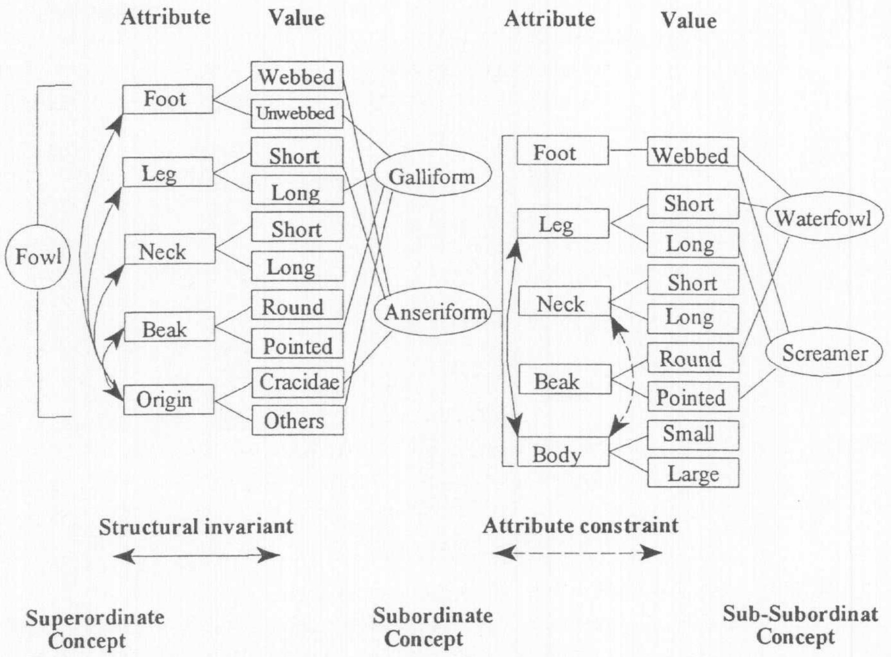

FIG. 5. A partial frame for "fowl", with revolutionary changes (constraints at the superordinate level are not shown in the figure).

new member in the contrast set, the new taxonomy is different from the old one, but there is no mismatch between them. All the objects classified by the old taxonomy are still separated with the same boundaries—"waterfowl" and "gamebird" are still contrasted with respect to the attributes of "beak", "body", "leg" and "foot". The newly introduced category "screamer" does not overlap with any one of the categories from the old taxonomy. Thus, individuals who adopt the new taxonomy may know novel uses of a new concept that adherents of the old taxonomy do not. But the latter can learn and accept the meaning of the new concept without encountering communication problems or incommensurability.

Now, suppose more anomalies occur: we learn that screamers share some very important features with waterfowl, for example, a common evolutionary origin. This anomaly will cause several important taxonomic changes. To accommodate this new discovery, a new attribute ("origin") and its related values are added to the frame of "fowl". From an evolutionary point of view, new structural invariants are formed, because "origin" determines all other attributes. New attribute and value constraints also emerge. Because they share the same evolutionary origin, "waterfowl" and "screamer" can no longer be separated; they have to be treated as one similarity class [9]. A new concept "anseriform" is thus introduced to denote both waterfowl and screamers, and "anseriform" and "galliform" constitute the new contrast set. To capture the differences between waterfowl and screamers, a new subordinate level is generated according to the frame of "anseriform" (Figure 5).

Unlike the previous taxonomic change, this one generates mismatches between the two taxonomies. Now "waterfowl" in the old taxonomy refers to objects that overlap those denoted by "anseriform" in the new taxonomy, which refers to both waterfowl and screamers. This overlap may cause communication problems between those who adopt different taxonomies. Individuals who continue to accept the old taxonomy may categorically deny some applications of concepts proposed by those who adopt the new taxonomy, such as using "anseriform" to refer to both waterfowl and screamers.

At this point, a revolutionary change in the concept "fowl" has occurred, but this revolutionary change has been achieved in a piecemeal fashion. Because of the strong attribute and value constraints within the frame of "fowl", every single anomaly can cause changes in the frame of the superordinate concept and then changes in the taxonomy. It is not merely changes at the observation level that are continuous, changes at the level of frame and of taxonomy are also continuous. Notice also that if this mechanism underlies a conceptual change in science there need be no psychological crisis preceding a revolution, since there is no accumulation of anomalies, and the revolutionary change need not occur instantaneously. The new taxonomy evolves smoothly, and becomes incompatible with the old one at a certain point in this piecemeal process.

The frame model clearly has the resources to permit continuous change in concepts as one pattern of scientific change. On the other hand, the frame model does not deny the possibility of discontinuity. When the constraints within concepts are weak, a single anomaly will not immediately cause taxonomic changes as described above. In such cases, conceptual changes in science will require an accumulation of anomalies, and exhibit a pattern of discontinuity, as discussed above under the feature-list model. The account of scientific change in terms of the dynamics of concept modification also leads naturally to a number of features of Kuhn's phase model that have been poorly understood. Using this account, several important features of Kuhn's account can be seen, not as inductive generalizations from episodes in the history of science, but as consequences of the dynamics involved in the change of human conceptual structures as described both by Kuhn and by recent cognitive science.

5. Conceptual divergence and crisis

Kuhn's account of concepts as determined by similarity and dissimilarity relations instead of necessary and sufficient conditions, leads directly to several key features of his phase model of scientific development. Like his account of concepts, these features have frequently been misunderstood. As a result, some philosophers have even questioned whether Kuhn's account can explain consensus and dissensus in science (e.g. Laudan (1984, pp. 17–19)). In the following we will show that not only is Kuhn's account of concepts capable of accounting for the emergence of dissensus, but that several features of the cyclical phase model of scientific change are consequences of this account of concepts. By contrast, traditional accounts of concepts have no comparable consequences.

In our previous paper, we explained that the use of similarity and dissimilarity relations allows different members of the same speech community to identify the same referents and non-referents of concepts by different criteria (Andersen *et al.*, 1996, pp. 355–356). Hence, individual differences between members of the same language community may exist, although they are not apparent in the usual linguistic practice. These differences are closely related to the graded structure of concepts. People applying different features in judging similarity and dissimilarity between category members will develop different graded structures for these categories.

Returning to our example of waterfowl, let us imagine a response to the discovery of screamers that initially classifies them *among* existing waterfowl. Suppose, for example, that Amy uses color and beak shape as her main criteria for identifying ducks. She will consider teal, which are brown, to be typical of the category "duck", and Chinese ducks, which are white, atypical. By contrast, Beth, who uses body size and beak as her main criteria, will find teal to be atypical and Chinese ducks to be moderately typical [10]. However, this difference between members of the speech community is not apparent in ordinary linguistic practice—the equivalent of normal science. All members agree that both Chinese ducks and teal are ducks and that they are neither geese nor swans.

Consensus is possible as long as the different criteria come from the same frame, so that both sides can learn more about the referents from each other without changing their classifications. However, the latent differences may come to notice when encountering new objects, like the "screamer" introduced in our earlier discussion of fowl. In this situation it may happen that one side makes a classification that the other flatly denies. Consider the responses of Amy and Beth to the screamer, with its duck-sized body and webbed feet, its long neck, and its chicken-like beak. Both of them will have a problem with the beak, but the webbed feet may incline them to classify the screamer as a waterfowl. Beth, who distinguishes ducks from geese and swans by their body size will have no trouble adding the screamer to the list of ducks she recognizes. Amy's case is more problematic. Unless the screamer is brown, she may have stronger reasons to classify the new bird as a swan or a goose. As body size is not a determining factor in the way she classifies ducks, the long neck and color may come into play as the decisive elements in her initial classification. Note that both parties are continuing to make classifications using the same conceptual system—the same frame for "fowl". Although in the past this system allowed them to classify all waterfowl (ducks, geese and swans) without any difficulty, the application of the same system to the newly discovered bird leads to contradictory results: Amy thinks it is a swan; Beth thinks it is a duck. Here the latent differences between Amy's and Beth's criteria for identifying ducks may come to the attention of their speech community for the first time. From this example we see how the frame model can establish the unequivocal use of concepts in consensus situations, but at the same time provide the resources to explain divergence in concept use and the appearance of dissensus. Later analysis reveals the latent divergences in the way Amy, Beth and their fellows employed the two concepts. These divergences led to divergent responses to anomalies, leading in turn to the revisions in taxonomy that are now the distinguishing feature of revolutions.

The example of a revolutionary change considered in Section 4 may be understood as a further instance of the same process. Initially, the response to the discovery of screamers was to introduce a new *sui generis* category at the same level as "waterfowl" and "game bird" (Figure 4). In this phase the crisis was latent. Let us suppose that the introduction of the new category concealed the divergence that Beth was identifying screamers using criteria that otherwise identified waterfowl but not game birds, while Charles was identifying screamers using criteria that otherwise identified game birds but not waterfowl. The introduction of new information about the common evolutionary origin of screamers and waterfowl obliges Beth's group to make its classification of the screamer as a waterfowl overt, and at this point Charles's group is obliged to adopt or reject the new taxonomic structure. On the assumption that the evolutionary reasoning behind the new classification is shared by the whole community, we would expect all parties to adopt the new classification, and a revolutionary change will have occurred in the category "fowl".

The frame representation of concepts provides a cognitive foundation for Kuhn's phase model of the development of science. The mechanism of conceptual divergence developed from Kuhn's account can explain the successive states of science specified in the model, and in particular the evolution from normal science to crisis. Here again, the feature-list model, in the form of either the classical or the prototype account, has clear liabilities. The classical account that defines concepts by lists of necessary and sufficient conditions does not indicate what to do if the lists turn out to be inadequate. If an anomaly is encountered, like the screamer in our example of waterfowl, the existing lists of necessary and sufficient conditions for defining waterfowl may have to be rejected entirely. In principle, if an anomaly clearly shows the inadequacy of a list of necessary and sufficient conditions, then the search for a new list must start from scratch [11]. The prototype account, on the other hand, can avoid a total collapse of an existing system, but it leads to another predicament. Without constraints between features, individuals would have unlimited options in responding to anomalies, and a community could disintegrate into fragments. If this happened, no organized research activities would be possible. Thus, both these feature-list accounts imply that, instead of leading to an ordered crisis state, anomalies would bring science back to a chaotic state similar to what Kuhn calls pre-normal science. If we consider the process just described at the community level, it corresponds to the collapse of a community.

By contrast, the frame model leads to quite different expectations. Anomalies will not lead to the total collapse of a scientific community, nor to a chaotic state. As illustrated by the example above, different individuals may use different criteria to classify the same objects. The appearance of an anomaly, such as that considered above, causes a scientific community to split. At the same time, because of the constraints between features, the number of possible responses to the anomalies allowed by the existing frame is limited. Consequently, when the community splits into several sub-groups, each categorizes the anomalies in their own way but all base their classifications on established conceptual systems [12]. Depending on the nature of the anomalies, individuals may recognize that they have been classifying objects by divergent features. This situation may lead to a general questioning of the established frame and taxonomy. Hence, Kuhn's theory of concepts, and the cognitive accounts we have considered that share the same features, explain how the consensus of normal science dissolves into crisis, but avoids total, unguided dissent. The limited dissent of the crisis phase, based on and determined by the previous conceptual scheme of the preceding phase of normal science, is critical for Kuhn's phase model of scientific development.

6. The no-overlap principle and taxonomic changes

Kuhn's account of concepts as determined by similarity and dissimilarity relations also implies that there is a hierarchical structure among concepts. On the one hand, objects are divided into groups according to their similarities in the process of conceptualization. On the other hand, dissimilarity relations require that all objects fall under one, and one only, of the concepts in question. If an object fell under two different concepts, it would no longer be possible to uphold the dissimilarity relation between these two concepts and they would coalesce. Hence, the primary property of a set of interrelated concepts is that the extensions of the concepts are not allowed to overlap. Kuhn highlighted this property by labeling it the *no-overlap principle*:

> [N]o two kind terms, no two terms with the kind label, may overlap in their referents unless they are related as species to genus. There are no dogs that are also cats, no gold rings that are also silver rings, and so on; that's what makes dogs, cats, silver, and gold each a kind. Therefore, if the members of a language community encounter a dog that's also a cat (or, more realistically, a creature like the duck-billed platypus), they cannot just enrich the set of category terms but must instead redesign a part of the taxonomy. (Kuhn, 1991, p. 4)

However, such a set of interrelated concepts is not any arbitrary group of non-overlapping concepts, but a set of contrasting concepts formed by the subdivision of a concept at the superordinate level. Because the instances of all the concepts in a contrast set form a family resemblance category at the superordinate level, these instances can be assumed to be more similar to each other than to instances of concepts outside the set. Hence, the instances of the concepts contrasting some given concept are exactly those "individuals ... to which the term might otherwise mistakenly be applied" (Kuhn, 1979, p. 413).

Similarity and dissimilarity relations also define contrast sets at the level of superordinates. Extending conceptual structure to higher levels, it follows from the no-overlap principle that all concepts in a contrast set are subordinates to the same superordinate concept, as otherwise some superordinate concepts would overlap. Hence, the conceptual structure established by the use of similarity and dissimilarity relations naturally forms a kind hierarchy (a taxonomic tree). The no-overlap principle for concepts in a contrast set thus implies a second principle: an inclusion principle for hierarchical structures which states that all instances of a given concept are also instances of its superordinate.

Kuhn believed that the no-overlap principle is fundamental for maintaining the stability of a conceptual system, and violations of this principle would eventually lead to a reconstruction of the existing taxonomy. "Periods in which a speech community does deploy overlapping kind-terms end in one of two ways: either one entirely displaces the other, or the community divides into two" (Kuhn, 1993, p. 319). In other words, the consequences of referential overlapping could be revolutionary, and violations of the no-overlap principle in some concepts could result in holistic changes in the whole conceptual structure.

The frame model can provide a cognitive foundation to understand Kuhn's insight about the consequences of referential overlap. Let us take the overlap between "waterfowl" and "anseriform" defined by the two successive frames (Figures 4 and 5) discussed in Section 4 as an example. Both "waterfowl" and "anseriform", as kind terms, are projectible in the sense that they support generalizations regarding their referents. With rich intraconceptual and interconceptual relations given by their frames, these two concepts also make room for generalizations regarding the referents of other concepts, particularly those from the same contrast set. Thus, calling a creature "anseriform" introduces one set of generalizations, covering waterfowl and screamers, as well as game birds; calling the same creature "waterfowl" introduces another set, also affecting the whole family of "fowl". Differences between these generalizations are not local and cannot be reduced to linguistic conventions. Instead, they represent holistic differences, and their incompatibility reflects differences in the matters of evidence and fact. In more realistic historical cases, these different generalizations are subject to incompatible natural laws, for instance, the overlap between the Aristotelian and Newtonian concepts of "force". In the case of an object moving in a vacuum under the influence of a force, the Newtonian generalization is that its velocity will increase gradually as the force accelerates the object. The Aristotelian generalization is that the velocity will immediately become infinite, due to the absence of the resistance that normally counterbalances the effect of motive forces. Thus, referential overlap, according to the frame representation, could jeopardize communication between members of the same speech community, and eventually lead to a reconstruction of the existing taxonomy.

If concepts were to be represented by feature lists, it would be more difficult, if not completely impossible, to interpret the consequences of referential overlapping. Without considering any intraconceptual and interconceptual relations, for example, it might be possible to isolate the overlap between "waterfowl" and "anseriform" in a local region. Since most referents of "anseriform" are referents of "waterfowl" and vice versa, and the only difference between them is that "anseriform" refers to a new creature (screamer) but "waterfowl" does not, it might be possible to reduce this overlap to merely a disagreement about linguistic conventions. To account for the revolutionary consequences of referential overlap, it would be necessary for the feature-list model to introduce additional assumptions regarding the relationship between concepts at different hierarchical levels and among those within the same contrast set. The feature-list model, however, does not indicate these interconceptual relations.

According to Kuhn, not all violations of the no-overlap principle are regarded as equally severe by the scientific community, and not all of them necessarily trigger holistic taxonomic changes. In Kuhn's phase model of scientific development, a crisis can have two possible outcomes: either leading to a revolution or returning to normal science. To understand these two possibilities, we need to analyze how graded structures and frames affect the recognition of anomalies.

As indicated in our previous paper, all human concepts show graded structures. Instead of a "flat" arrangement in which all referents are equally good examples, all concepts have best examples, with other examples varying on a continuous scale of typicality. These graded structures explain the different possible outcomes for anomalies, or violations of the no-overlap principle. Specifically, whether an anomaly is solvable within the existing taxonomy or requires a revolutionary shift in the conceptual structure depends upon where the overlap occurs, that is, whether the overlap happens in the prototypes of the related concepts. When we find that bats, which are regarded by many human cultures as an atypical example of "bird", share important mammalian features and can also be regarded as a moderately good example of "mammal", an overlap occurs in the examples of the two concepts, but outside the prototypes. Because the problematic case bears little resemblance to the prototypes, this overlap causes little trouble to either concept, and the existing taxonomy remains more or less unaffected. Instead of changing existing systems, responses to this overlap may suggest new features relevant to the existing relations and thereby enrich the two existing concepts. In contrast, suppose that one day we discover creatures that look like robins, which in the US are regarded as one of the best examples of "bird" (Barsalou & Sewell, 1984, pp. 15–20), but also share important features with mammals, so that they can also be regarded as good examples of "mammal". Then an overlap would occur in the prototypes or the good examples of the two categories. This overlap would force us to change both the concept of "bird" and that of "mammal". Eventually the whole taxonomy of "living thing" would have to be adjusted and a revolutionary shift would be inevitable.

The internal structures of concepts described by frames also play a critical role in determining the outcome of anomalies. As mentioned in previous sections, not all features within a concept are equal. Some features are attributes and some are merely values of attributes. Even among attributes, some are more important or more fundamental because they can affect the values of some others through structural invariants and constraints. For example, in the last partial frame of "fowl" described above (Figure 5), the attribute "origin" is fundamental because, from an evolutionary point of view, it constrains the values of all other attributes. These internal structures can cause different responses to violations of the no-overlap principle. Whether an anomaly requires a revolutionary change depends also on whether the overlap happens in the fundamental attributes of the related concepts. Suppose that one day we discover that some birds, say, ostriches, have the same immediate evolutionary origin as apes. Since ostriches are not a typical example of "bird", the overlap between "bird" and "mammal" does not occur in their prototypes. But this discovery could threaten the existing conceptual systems, because the overlap involves fundamental attributes ("origin") in both concepts. It might imply that apes, or even humans, evolved from birds. This overlap, if true, would force us to change both the concept of "bird" and that of "mammal". Thus, an overlap between atypical examples can also incite revolutionary changes, provided the overlap involves fundamental attributes of the related concepts.

It is clear that there is no sharp boundary between anomalies that may cause revolutionary shifts and those that may not, because both the typicality of examples and the importance of attributes vary on a continuous scale. Thus, violations of the no-overlap principle form a spectrum: some may cause holistic and revolutionary shifts of the conceptual structure, some may cause only a few minor changes, and others intermediate degrees of alteration. Further, because members of the same speech community may select different prototypes for the same concept and may give different weights to the same attribute, reactions to anomalies may be quite different within the same community. In this way, members of the same speech community may have different judgements about the severity of anomalies [13]. Again, these differences will not be clear-cut, but a matter of degree.

7. Conclusion

It should now be clear that the mature form of Kuhn's theory of scientific revolutions is built upon his theory of concepts. Many key features of Kuhn's theory, such as the emergence of crisis from normal science, the possible consequences of crisis, and the holistic nature of taxonomic changes, can be understood as consequences of those features of conceptual systems that Kuhn describes by means of similarity and dissimilarity relations, but at odds with the classical account of concepts. This goes some way towards explaining Kuhn's repeated complaint that his theory of scientific revolutions has been misunderstood by philosophers of science, many of whom still subscribe to the classical account of human concepts.

Kuhn's cyclical model of the history of science (Figure 1) may be presented in outline as a historical sequence of phases: the normal science phase generates anomalies, which (sometimes) lead to a crisis phase, which (sometimes) leads to a revolution, leading to a new phase of normal science. In the light of Kuhn's mature work and the connections we have enumerated to modern psychology and cognitive science, we suggest a new, cognitive reading of this model. Normal science is not so much a state of universal agreement as a state in which conceptual divergences (like those considered in Section 5) are latent rather than overt. An anomaly is a new phenomenon that makes the latent divergences apparent, and a serious anomaly differs from a minor one in the extent to which it makes these differences overt, and in the degree of change its resolution brings about in the existing conceptual structure. The severity of an anomaly may be correlated with the typicality of the phenomenon it represents as an instance of the concepts involved: anomalies involving prototypes or fundamental attributes will be the most severe. Anomalies that can be resolved without taxonomic changes (that is without reforming similarity and difference classes) lead to a resumption of normal science. Anomalies that require taxonomic changes for their resolution create the episodes called scientific revolutions, and lead to new normal science traditions that use the conceptual structures introduced by the revised taxonomy.

As we have shown above, the splitting of a scientific community that occurs during a crisis phase may be seen as a consequence of possibilities latent in the conceptual structure it adopts during the normal science phase. Many features of this conceptual change may be illuminated with the aid of work on graded structures supported by both the feature-list model (augmented by prototypes) and the frame model. But not all cognitive accounts of concepts are equal here. Our analyses of the formation of conceptual divergence, the consequences of crisis, and the patterns of revolutionary change show that the frame model provides a more detailed and more general cognitive explanation of scientific change than the feature-list model. The frame model is superior both because it describes the process of taxonomic changes at the conceptual rather than at the behavioral level, and because it allows both continuity and discontinuity as possible patterns of change during scientific revolutions.

We conclude by suggesting another important implication of the frame model. For many years philosophers of science have viewed incommensurability as a liability of any account of science. With the frame representation, however, we can show that, far from being a liability, incommensurability plays a very important, positive role in the evolution of science.

According to the feature-list representation of concepts (presented in Section 3), the key to paradigm shifts is taking a different point of view, that is, adopting a new cultural or theoretical stereotype, and then constructing new prototypes of major concepts accordingly. This feature-list model thus implies that individuals can switch between different points of view whenever they want, just like the gestalt switches that Kuhn used to first explain incommensurability. As the feature-list model lacks structural relations built among the features that constitute prototypes, concepts from an old paradigm can be broken into discrete features. These discrete features may still be understandable under the new paradigm, provided there is a certain degree of overlap between the knowledge bases of the rivals. Consequently, the feature-list representation implies that scientists may be able to revert back to the old paradigm even after a revolution. This process might even be considered as a way for individuals to enlarge their vocabulary by switching between rival paradigms. Thus, according to the feature-list model, scientific change is hardly unidirectional.

The frame model, however, significantly reduces the role of cultural and theoretical stereotypes in the process of taxonomic change. According to the frame representation of concepts, we construct new prototypes by assigning different sets of values to the attributes of the related frame (Barsalou, 1992). Thus, we are not completely free when we revise the existing conceptual system. The structural connections within the existing frame will limit our options. Undoubtedly, some structural relations within frames reflect our cultural and theoretical beliefs as well as our goals. But many more structural relations are independent of our cultural and theoretical stereotypes. In the original frame of "fowl" (Figure 3), for example, the structural invariant between "body" and "neck" is physical, and the constraint between "beak" and "foot" is imposed by nature. Even if we want to change a frame according to a newly adopted point of view, we are constrained by the structural relations demanded by the environment. Thus, in practice, alterations in frames are usually induced and guided by anomalies, that is, by changes in the environment.

Without further significant changes in the environment, of the kind needed to generate anomalies, scientists seldom revert back to an old frame after they have accepted a new one.

Furthermore, the rich structural information within frames, together with the related taxonomic structure and similarity relations, will make direct translation between the new frame and the old one impossible. The relations between frames from different taxonomies are similar to those between different languages. It is impossible to understand a new language by simply replacing words in the foreign language by words in our own, but we can make sense of a significant portion of a foreign language by relating it to *its own linguistic context*, rather than to our native language (Kuhn, 1983a, pp. 672–673). We become bilingual through a process of language add-on: we acquire a new frame that is separate from the old one, and there is no superordinate frame that incorporates the two (Kuhn, 1990b, p. 308). But bilingualism has its price. Bilingual individuals frequently report that there are things they can express in one language but not in the other. Although bilinguals can speak two different languages, terms learned from the old language may not be projectible in the new one. In such cases, bilingualism does not improve the effectiveness of language use, nor the efficiency of problem solving. If we conceptualize the relations between successive paradigms in this way, although individuals could in principle switch between different paradigms through a process of language add-on, they would gain nothing from doing so, and they would lose the advantage of the new paradigm always advertised as decisive by Kuhn: its ability to deal with the anomaly that brought the old paradigm to crisis.

The frame interpretation of concepts thus denies gestalt switches triggered by adopting different points of view as the dominant pattern of conceptual change. Instead, conceptual change is usually unidirectional: after scientists adopt a new paradigm, they seldom go back to the old one. The unidirectional feature of scientific evolution thus gives a whole new meaning to incommensurability. To ensure growth in a certain direction, a conceptual disparity between successive taxonomies or paradigms is needed. It makes switches between paradigms difficult and valueless. By causing translation difficulties or communication obstacles, incommensurability functions as such a disparity, and thus encourages the unidirectional evolution of human knowledge. Thus, according to the frame model, incommensurability is no longer a liability. It is indispensable for the evolution of science.

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Notes

[1] This project is a collaboration in which all authors contributed equally. The order of authors' names does not indicate different levels of contribution to the project.

[2] A number of philosophers of science have explored the implications of the frame model. Thagard (1992) develops a computational theory of conceptual change on the grounds of a conceptual system that represents concepts in terms of complex structures akin to frames. In their discussion of realism, Aronson *et al.* (1995) use a frame-like representation of concepts to develop a new metaphysics, emphasizing the importance of relational properties.

[3] Kuhn's kind-concept clearly went beyond the one defined by the traditional theory of natural kinds. He also disagreed with Hacking, who suggested that Kuhn should adopt a notion of "scientific kinds", that is, kinds that scientific communities find relevant to their research (Hacking, 1993, p. 290). Kuhn preferred a more general concept of kinds—things that trace a worldline through space and time and that can be re-identified by cognitive mechanisms. In many respects, they are similar to what Aristotle called "substances". See Kuhn (1993, p. 315; 1990a, pp. 11–14).

[4] The same kind of phenomenon also exists among different sub-cultural groups. In another experiment conducted by Barsalou and Sewell, three different sub-cultural groups—university faculty, graduate students, and undergraduate students—established dissimilar prototypes and assigned different meanings to a series of concepts. See Barsalou & Sewell (1984, pp. 26–33).

[5] This is an example of a general constraint on conceptual structures discussed below—the no-overlap principle.

[6] Barsalou originally assumes that knowledge bases consisted of linguistic symbols (Barsalou & Sewell, 1984), but recently he has suggested that they consist of perceptual representations (Barsalou, 1993). The difference between these two interpretations is significant, but addressing this issue is beyond the scope of our paper.

[7] An example of intentional limitations is the process of optimization, in which human agents select desirable values of attributes according to their goals (Barsalou, 1992, p. 39). This implies that significant communication difficulties or incommensurability would occur between agents with different goals. For more discussion of incommensurability of this kind, see Chen (1994).

[8] In theory, it might be possible to generate the same set of value assignments through random selections from a list of features. But this would make taxonomic change into a random process, contrary to our understanding of the history of science. In contrast, the frame model generates this set of value assignments according to the structural relations and constraints defined by the frame. Thus, the frame account can provide a better understanding of taxonomic change than the feature-list model.

[9] Note that concepts are defined by examples rather than by definitions. Thus, a bird with Cracidae origin and round beak (swan) is a good example of "anseriform", and a bird with Cracidae origin but pointed beak (screamer) can still be a moderately good example of "anseriform". For more on this aspect of concepts see Andersen *et al.* (1996, pp. 349ff).

[10] Chinese ducks, or Pekin ducks, are white, with a round beak and a medium size body; teal are brown (males may have colored heads or wing flashes), with a round beak and very small bodies.

[11] Dreyfus (1993, p. 199) uses similar arguments against traditional rule-based artificial intelligence.

[12] McClelland (1986, pp. 531–546), and Churchland (1989, pp. 153–196) use similar arguments when they advocate connectionist networks to overcome the problems faced by traditional artificial intelligence.

[13] Many other factors influence such judgements. See Kuhn (1977, pp. 320–339; 1983b) and Hoyningen-Huene (1992, 1993, Ch. 7.4).

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