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Kuhn's mature philosophy of science and cognitive psychology

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ABSTRACT *Drawing on the results of modern psychology and cognitive science we suggest that the traditional theory of concepts is no longer tenable, and that the alternative account proposed by Kuhn may now be seen to have independent empirical support quite apart from its success as part of an account of scientific change. We suggest that these mechanisms can also be understood as special cases of general cognitive structures revealed by cognitive science. Against this background, incommensurability is not an insurmountable obstacle to accepting Kuhn's position, as many philosophers of science still believe. Rather it becomes a natural consequence of cognitive structures that appear in all human beings.*

1. Introduction

From very early in his long career Kuhn has sketched, and progressively filled in, a consistent picture of science, the nature of concepts, and the nature of knowledge. But many of the definite claims he makes about the nature of concepts, and hence the nature of knowledge, are uncongenial to philosophers of science. It is not our aim in this paper to show that Kuhn has a coherent and systematic account of concepts and human knowledge, of which science is the most important example. This has already been done by Paul Hoyningen-Huene in his 1993 book Reconstructing Scientific Revolutions. Taking this exposition as a reliable account of the mature Kuhn, our aim is to show that the most radical features of Kuhn's account are independently supported by recent research in cognitive science, and especially cognitive psychology [1]. The demand for a naturalized epistemology has been heard for several decades in philosophy and philosophy of science. In the last decade, philosophers and philosophers of science have moved strongly into cognitive science, either to construct new philosophical accounts of scientific change (Nersessian 1987, 1994; Thagard 1992) or applying its resources directly (Solomon 1992). But, paradoxically, philosophers of science and others continue to dismiss or undervalue the account of science that may most readily be presented as naturalized, on the grounds that it is the most directly supported by results

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in cognitive science. By presenting Kuhn's mature position as clearly as possible, and displaying the support that it now derives from cognitive science, we hope to liberate the resources of Kuhn's account for general philosophical use, while advancing the program of naturalized epistemology.

Our main concern will be the theory of concepts, concluding with a brief consideration of the mechanism of conceptual change during scientific revolutions and the nature of incommensurability. Drawing on the results of modern psychology and cognitive science we will suggest that the traditional theory of concepts is no longer tenable, and that the alternative account proposed by Kuhn may now be seen to have independent empirical support quite apart from its success as part of an account of scientific change. We suggest that these mechanisms can also be understood as special cases of general cognitive structures revealed by cognitive science. Against this background, incommensurability is not an insurmountable obstacle to accepting Kuhn's position, as many philosophers of science still believe. Rather it becomes a natural consequence of cognitive structures that appear in all human beings.

2. Wittgenstein's challenge to the received account of concepts

In the English-speaking philosophical tradition it is customary to define a concept by its intention or its extension. The extension is the class of objects falling under the concept (in some perhaps very general sense of "object"). The intention of a concept is a list of features, specified by other concepts, that all objects falling under the concept share, in contrast to objects that do not fall under the concept. In a definition of the concept, these features, or subsidiary concepts, will be listed in the definiens, as a set of individually necessary and jointly sufficient conditions. Satisfying these conditions assures that an object possessing the corresponding features falls under the concept. In the Western philosophical tradition much attention has been devoted to the task of finding plausible candidates for such necessary and sufficient conditions.

As a broad, but fairly exact generalization, it is true to say that this view of concepts was universal, in the Western philosophical tradition, and related fields such as psychology, until the mid 1970s. There were only two important exceptions: the mature Wittgenstein, and the young Kuhn.

Wittgenstein (Wittgenstein 1958, §67 ff.) had proposed that the instances of a concept like "game" might bear no more than a family resemblance to one another. He clearly envisaged a situation in which although the first instance of a concept shared some common features with the second, the second shared different features with the third. In such situations, although it was true that all objects falling under the concept shared some features with their fellows, no single feature or set of features had to be common to all the objects. It would clearly be impossible to define such a concept using necessary and sufficient conditions. If relations among objects are what constitute concepts, then what constituted these concepts would be the network of overlapping and crisscrossing relations, and these might be unique for every concept. The integrity of such a concept is the integrity of its pattern. This does not make family resemblance concepts inferior to those definable by necessary and sufficient conditions, any more than a rope made of a great many short overlapping fibers is inferior to one with single fibers running from end to end (although, like such ropes, they may be useful for different purposes).

Philosophical responses to Wittgenstein's account of family resemblance concepts ranged from polite bafflement to indignant rejection (Baker and Hacker 1980, 332-337). Even if the existence of such concepts was admitted, it was generally assumed that concepts definable by necessary and sufficient conditions were more important, and that the concepts of most interest to philosophers, and especially concepts in the exact sciences, were of this type. This response may have contributed to the difficulty in assimilating Kuhn's original presentation of his ideas. In The Structure of Scientific Revolutions Kuhn adopted Wittgenstein's account of family resemblance concepts (Kuhn 1970, 44-6. See also Hoyningen-Huene 1993, Ch. 3.6.f), and suggested that research based on paradigms (here clearly to be understood in the sense that would later be labelled "exemplar") may share a family resemblance rather than being related by specific rules of methodology. In doing so he was also suggesting that family resemblance concepts might appear in the domain that other philosophers of science were most concerned to exclude them from. This became still clearer -- and more threatening -- in the 1970 Postscript, where Kuhn suggested that the variants of Newton's second law applicable to different physical systems shared a family resemblance, but no single defining common properties. This suggested that the most central examples of scientific concepts might turn out to be family resemblance concepts rather than the well behaved necessary and sufficient condition concepts desired by earlier philosophers of science.

3. **Kuhn's theory of concepts**

Beginning in the 1969 Postscript to Structure, Kuhn emphasized that exemplars, rather than disciplinary matrices or worldviews, are the primary sense of paradigm. The elaboration of his views on exemplars led him to develop a sophisticated account of concepts and the nature of empirical knowledge. Exemplars are the vehicle by means of which new members of the scientific community acquire scientific concepts. According to this theory, the basic conceptual structure of science is a grouping of objects into similarity classes corresponding to the extensions of concepts. This grouping is achieved by learning to identify similarities and dissimilarities between the objects. When Kuhn gives examples of these relations of similarity and dissimilarity, it becomes apparent that the objects in similarity classes need bear no more than a family resemblance to their fellows, and hence that the concepts corresponding to these similarity classes are family resemblance concepts. Although Kuhn no longer uses the term "family resemblance" to make his case, it is apparent that in his later account of concepts and conceptual structure, family resemblance enters his account of the nature of science and the nature of knowledge at the most basic level.

One learns a concept by being guided through a series of encounters with objects that highlight the relations of similarity and dissimilarity currently accepted by a particular community of concept users. Teaching and learning depend upon examining similar or dissimilar features of a range of objects (Kuhn 1974, 1979. See also Hoyningen-Huene 1993, Ch. 3.6). Kuhn's standard example is the child learning to distinguish ducks, geese, and swans. In the learning process the child is shown various instances of all three categories, being told for each instance whether it is a duck, a goose or a swan. Also, the child is encouraged to try to point out instances of the categories. At the beginning of this process the child will make mistakes, for example mistaking a goose for a swan. In such cases the child will be told the correct category for the instance pointed out, perhaps by drawing attention to some feature that distinguishes this bird from swans. In other cases the child ascribes the instance pointed out to the correct category, and is told so. After a number of these encounters the child has acquired the ability to identify ducks, geese, and swans to the satisfaction of the instructor. As Kuhn emphasizes, in such a learning process "the primary pedagogic tool is ostension. Phrases like "all swans are white" may play a role, but they need not," (Kuhn 1974, 309).

Kuhn's description of grouping objects into similarity classes is not restricted to cases like children learning waterfowl, but applies to adult scientific concepts as well. Ptolemaic astronomers might learn the concepts "star" and "planet" by having the Sun, the Moon, and Mars pointed out as instances of the concept "planet" and some fixed stars as instances of the concept "star". Similarly, Copernicans might learn the concepts "star", "planet", and "satellites" by having Mars and Jupiter pointed out as instances of the concept "planet", the Moon as an instance of the concept "satellite" and the Sun and some fixed stars as instances of the concept "star". As with the child learning to distinguish ducks, geese, and swans, a major part of the learning process consists of instances being ascribed to or excluded from the categories to be learned.

Nothing limits the possible characteristics according to which the objects may be similar or dissimilar. On the contrary, anything one knows about the referents can be used when matching them with terms (Kuhn 1983a). This also means -- in contrast to the traditional view -- that although different speakers use a given concept to pick out the same similarity class, they need not identify instances and non-instances by the same features. The child learning to distinguish ducks, geese, and swans may identify them by a combination of their colors and beak shapes. The teacher may use beak shape and length of neck. A third person might use length of neck and body size, or any other feature that distinguishes ducks from geese and swans. In principle, different individuals may use totally different features to define the same similarity class. Although the similarity classes "duck", "goose", and "swan" may be imagined to have homogeneous members, a moment's thought will show that the members of these classes -- individual ducks, for example -- bear no more than a family resemblance to each other. Indeed individuals like these (and individual human beings) are paradigmatic of the sort of objects among which we recognize family resemblances. Given the differences in identification procedure for the three classes used by the child and the two adults as outlined above, the class of these classes (here perhaps "waterfowl") also clearly corresponds to a family resemblance concept.

Dissimilarity plays as important a role as similarity in establishing similarity classes. Attempting to determine a category by similarity alone would be attempting to determine the category solely by what the objects have in common. Such an attempt would fail for the very same reasons that necessary and sufficient conditions fail. Categories may exist where different pairs of members have different things in common, and some members may even have some of these things in common with members of other categories. Thus, similarity alone cannot do the job. Instead, relations of dissimilarity must be included as well. These separate members of the category from objects in other categories to which they could otherwise mistakenly have been assigned. For the child learning to distinguish ducks, geese, and swans, it is not enough to note that ducks have similar beaks or similar colors. Wild ducks and geese have the color brown in common. Domestic ducks have the color white in common, and the latter color in common with domestic geese. Differences between, for example, duck beaks and goose beaks, or the sizes of ducks and geese, are as important as the similarities among ducks if the child is to be able to distinguish geese from ducks. Hence, concepts have to be learned in clusters of contrasting categories called contrast sets.

To sum up, according to Kuhn the similarity classes underlying conceptual structure are acquired through exposure to instances of members and non-members of the classes. However, this exposure to members and non-members does not create anything like a description of unique features determining membership or non-membership, but constitutes similarity classes linked solely by family resemblance. This is a perfectly general account of concepts. It includes both everyday and scientific concepts, both of which are to be understood in a new way. In rejecting a specific list of features as the basis for similarity and dissimilarity judgements, Kuhn rejects the traditional view that concepts can be defined by necessary and sufficient conditions (Kuhn 1979, 1983a, 1983b. See also Hoyningen-Huene 1993, ch. 3.6.f).

4. **Rosch's empirical vindication of family resemblance**

The rejection by Wittgenstein, and later by Kuhn, of the traditional view that concepts can be defined by necessary and sufficient conditions, came into psychology in the mid-1970s by the research carried out by Eleanor Rosch and her collaborators. It is difficult to convey to philosophers the completeness of the change in psychologists' theories of concepts brought about by this work. Although there were studies prior to Rosch's that indicated similar effects (for a review see Lakoff 1987: 12-39), it is generally acknowledged that the work of Rosch and her collaborators was primarily responsible for dis-establishing the account of concepts based on necessary and sufficient conditions, and replacing it with a consensus view that is basically Wittgenstein's, even if its detailed structure is still a matter for debate. These events are regularly referred to as the Roschian Revolution. Whatever disagreements remain on the positive account that is to replace the discredited view, there is a remarkable degree of unanimity among contemporary psychologists that the previous view is now indefensible. The single strongest piece of evidence supporting this conclusion is the demonstration of graded structure as a universal feature of human concepts.

A generally unrecognized consequence of the traditional view that concepts can be defined by necessary and sufficient conditions is 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 hence are all equal as instances of the concept. On this view, then, it makes no sense to suggest that a particular object is a better example of the concept than another. But empirical research reveals quite the opposite. Human beings regularly and reliably grade instances of a concept as bad, better, and best examples. All instances fit somewhere on a spectrum that varies in "goodness of example". This variation in the status of instances is called a concept's "graded structure."

Beginning in the early 1970s, Eleanor Rosch (who before 1973 published as E. R. Heider) showed that not all samples of a color were treated as equally good examples. Working with the Dani, a tribe in New Guinea, Rosch showed that her subjects reliably selected particular color samples as the best example of a color, even when they lacked a name for the color in their language. In a series of ground-breaking papers, Rosch connected this result to Wittgenstein's idea that not all objects falling under a concept need to share a single common feature, and extended the result from perceptual categories to common semantic categories -- the basis for Wittgenstein's original work.

The basic result corroborated again and again by the studies of Rosch, and those who followed her, was that all human concepts show graded structure. Instead of a "flat" category in which all members are equally good examples, the empirical results showed that all categories had best examples, with other members varying on a continuous scale of "goodness of example"[2]. The existence of best examples, and continuous gradations from good to bad in other examples of a concept, shows 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.

Rosch demonstrated the existence of graded structures in perceptual categories involving color samples and simple geometrical shapes, and semantic categories like tools, clothing, furniture, animals, trees, fish and birds (Heider 1972, Rosch 1973a,b, Rosch and Mervis 1975, Rosch et al. 1976). The same result was established for facial expressions (Ekman et al. 1972), locatives (Erreich and Valian 1979), psychiatric classifications (Cantor et al. 1980), polygons (Williams et al. 1977), 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). Even number concepts were shown to have graded structures (Armstrong et al, 1983; for a discussion see Lakoff 1987, 148-151).

Although Rosch herself was initially inclined to identify the concept with the extended graded structure defined by its instances, by the late 1970s she recognized that the ever broadening data on concepts and categorization required concepts to have a complex internal structure. Goodness-of-example ratings were only one aspect of this total structure. At present there is wide agreement that concepts, categories and semantic fields are structured by something beyond the features of the instances themselves. These factors also deserve to be considered part of what counts as a concept for human beings. Such factors are often referred to as "theoretical" principles or "theories", especially when they have causal or explanatory force (Medin & Smith 1984). Keil (1987), for example, shows the pervasive influence of what he calls "theories" on the development of concepts -- and especially graded structure -- in even the youngest children. Other people prefer to account for these factors as cognitive models (Lakoff 1987). One account that accommodates all the current empirical data and that has many useful features for understanding the historical development of science is the dynamic frame model proposed by Barsalou (1992a). An attractive feature of this account is that it permits the recovery of many features of Kuhn's account of concepts, and scientific change, as particular cases of a more general model.

5. **Dynamic frames, concepts and incommensurability**

Frames are intended to represent the structure of the most fundamental level in human cognition [3]. Fig. 1 shows a partial frame for the central concept in the teaching-learning scenario described by Kuhn. The frame has three important features:

- First, the relations between some of the elements appear in all instantiations of the frame, and are therefore structural invariants. In the frame of "bird", a neck is always associated with a beak, for example.
- Second, some elements give values of other elements called attributes. Hence, not all features of an object are equal: some are values of others. It is important not to allow philosophical prejudices to intrude at this point. Although the relation between attribute and value may be instantiation, or exemplification, there is no restriction on the nature of attribute-value links. Similarly, the links between concepts and attributes need not be homogeneous. This is particularly important in understanding the links between elements forming structural invariants, which may be sui generis. While "neck" and "beak" are attributes that are parts of a bird, color is not a "part" in the same sense, and "size" and "gait" are clearly not parts at all.

  The flexibility required by Kuhn when he insists that any feature of an object can be used as the basis for grouping it into similarity classes with other objects appears as two features of the frame account. The first is the diversity of possible links between a concept ("bird") and its attributes ("color", "neck length", "gait"). Second, any given individual need not instantiate the whole of a frame. The frame of a concept is a theoretical representation structuring all possible information connected with a given concept in a speech community. Individual speakers may only know part of this information, but still use the concept correctly. Kuhn's claim that any feature of an object can be used as a basis for grouping it into similarity classes corresponds to

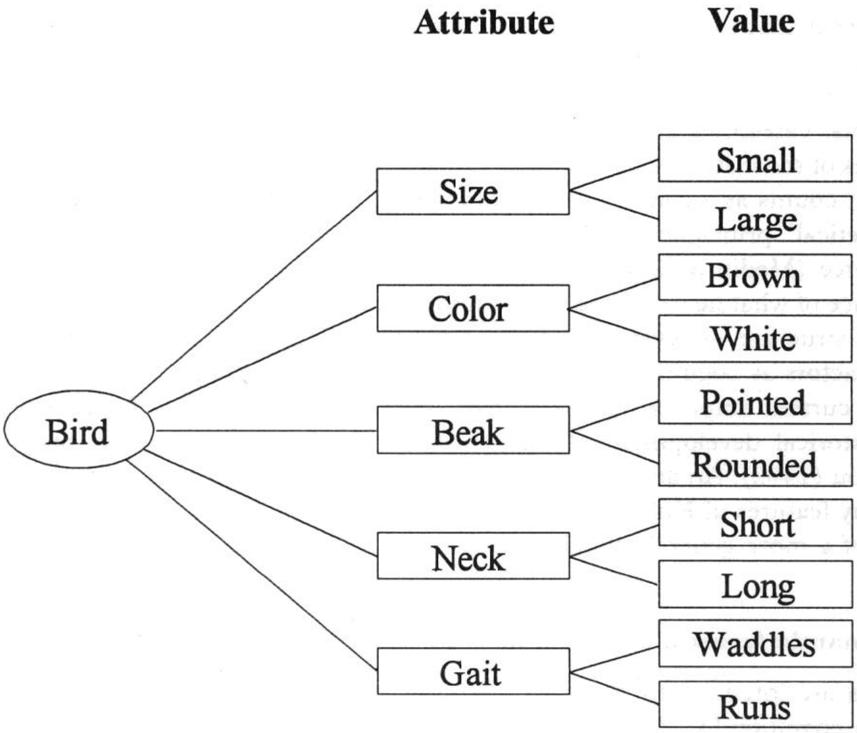

FIG. 1. Partial frame for "bird".

the claim that there is no restriction on which part of the community defined frame must be instantiated by an individual.

- Third, attributes, values, and other aspects of frames are subject to a variety of constraints. For simplicity, let us consider only value constraints, as an example. Starting from the "bird" frame (Fig. 1), to produce a frame for a particular type of bird, for example a goose (Fig. 2), we distribute values across the attributes of the initial frame. However, our choices are not entirely free. Confining our attention to wild waterfowl, if we select "long" as the value for "neck", we are obliged to select "large" for "body size". This is not a logical compulsion. Rather, our community's concepts of ducks, geese, and swans are such that these are the only choices we have.

The frame model of concepts supports the existence of graded structures. Earlier work by Barsalou and Sewell, using a version of prototype theory, cast considerable doubt on the idea that concepts are stable structures that are simply retreived from long term memory when needed. Instead, they suggested that concepts may be constructed instantly in the working memory when they are needed (Barsalou and Sewell 1984, 36-46; see also Barsalou 1987). Based on results like these, some researchers concluded that graded structures reflect primarily differences in performance rather than in judgment. This encouraged them to believe that graded structures would disappear if we consider the essential information that makes up conceptual cores, and they continued to prefer the

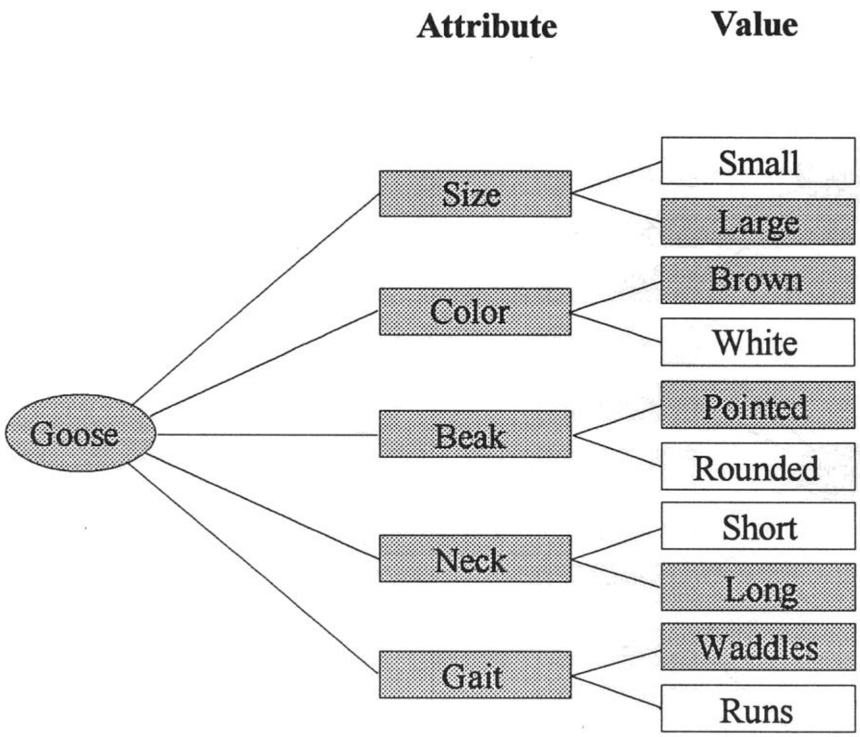

FIG. 2. Partial frame for "goose".

traditional account of concepts in the face of the Roschian revolution (Rey 1985: cf. Armstrong, Gleitman and Gleitman 1983). The frame model, however, shows that graded structures still exist when essential information from conceptual cores is taken into consideration. In this model, a concept is generated according to a fundamental representational structure -- its frame. The hierarchical relations between attributes and values within a frame make it possible that a concept is represented by many different value combinations. Except in some extreme cases where strong connections exist among all attributes and their values, a frame seldom reduces possible value combinations to a single set. A concept usually has many different exemplars. A graded structure thus emerges naturally among the possible exemplars: those that appear most frequently (or those that are best suited to achieve the goal served by the concept) become the prototype (Barsalou, 1992a, 1993a) [4].

What Kuhn calls similarity and dissimilarity relations are not depicted directly in frame diagrams. Rather they are implicit in the recognition of a contrast between the different values that a given attribute can take. Recognizing similarities and dissimilarities between objects on the basis of the values taken by specific attributes is how we group objects into similarity classes ("duck", "goose", etc.). In a frame representation, this comparison is made between frames. Using this notation it is easy to construct a diagram showing how different individuals may successfully pick out the same similarity classes while using similarity and dissimilarity relations that have no

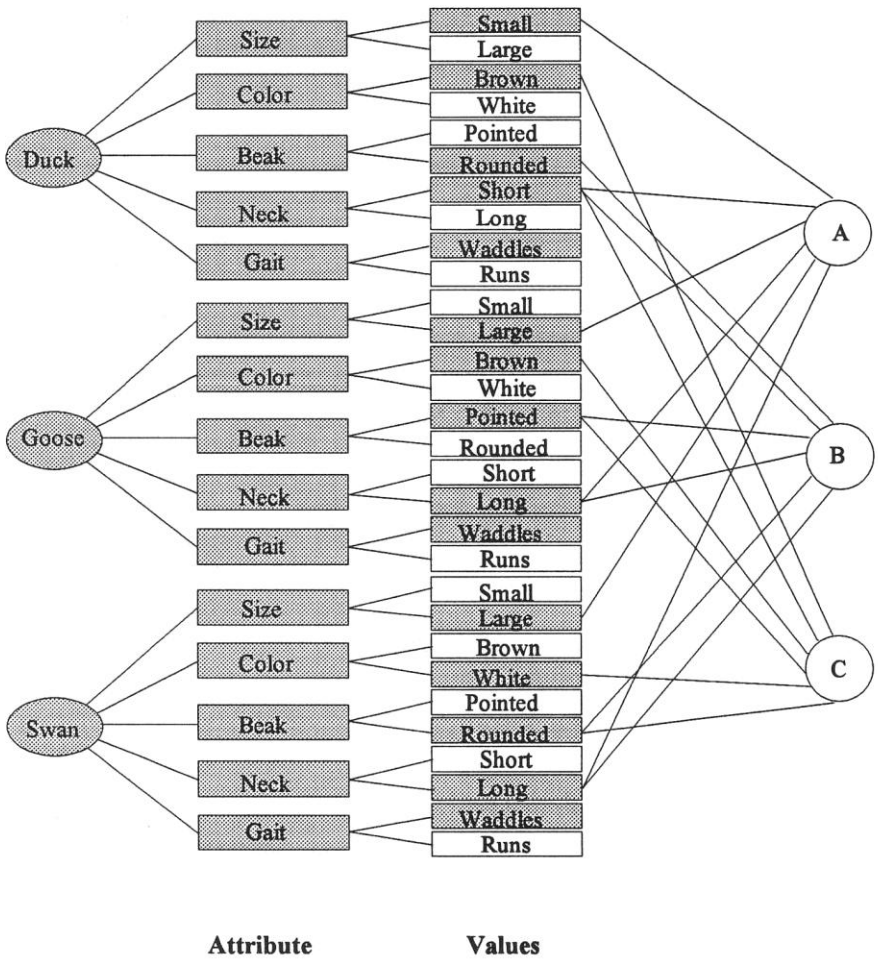

FIG. 3. Three different individuals, A, B, C, may use similarity-difference relations with no single common member to group objects successfully into equivalence classes. Here radial lines indicate *attributes* used by each individual. Comparison of attribute values *between frames* is equivalent to similarity-dissimilarity judgements in Kuhn's sense.

single common feature (Fig. 3). Thus, the increasingly strong support for frames as the primary vehicle for human cognition of concepts naturally includes support for a view of concepts in terms of family resemblance, and also Kuhn's account of concept acquisition in terms of similarity and dissimilarity relations, while excluding concepts defined through necessary and sufficient conditions. Although the latter may be respectable in limited contexts and for special purposes, family resemblance concepts are the human norm [5].

In his latest work Kuhn redraws the picture of scientific revolutions (Kuhn 1983a, 1991). Changes in taxonomy capture the revolutionary features of paradigm shifts, and the most important changes during scientific revolutions can now be conceptualized as taxonomic shifts. The role of taxonomy is not simply linguistic, but also cognitive.

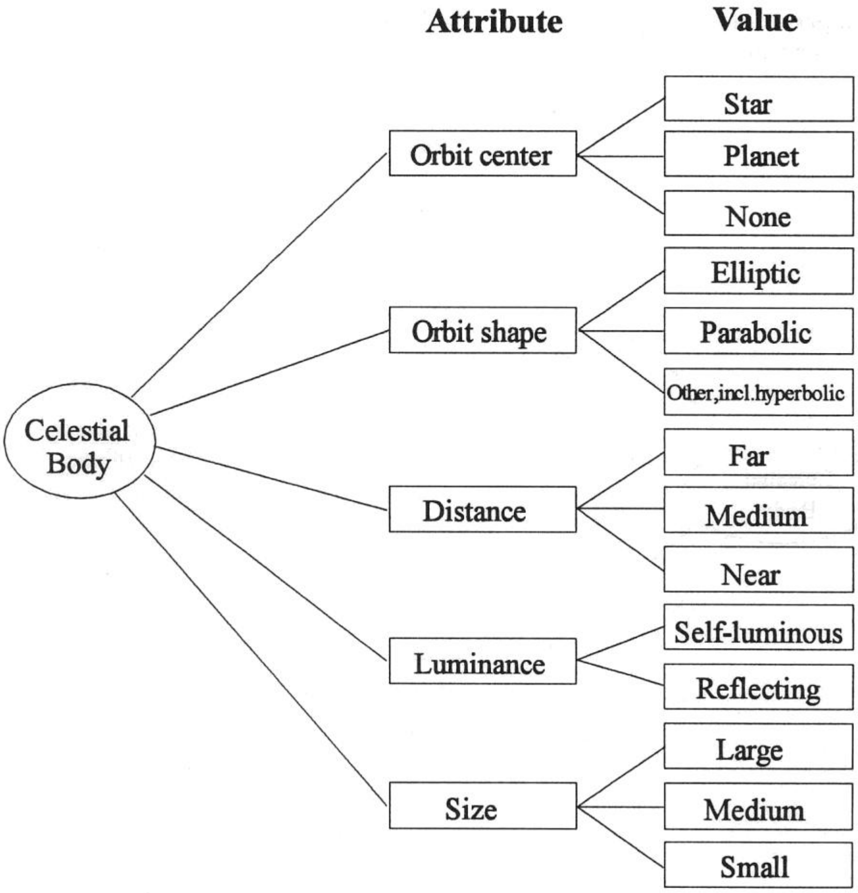

FIG. 4. Partial frame for "celestial body", c. 1700.

From a cognitive point of view, a taxonomy is a specific structure in the conceptual field defined by a frame. Consider the conceptual field defined by the frame of "celestial body" according to seventeenth century astronomy (Fig. 4). This frame has a number of attributes, each of which can have different values. For purposes of illustration we select only five attributes. Thus, this frame generates a conceptual field that would have 162 potential concepts (3x3x2x3x3), although not all of them are physically possible, that is, some of the 162 potential value combinations are not found empirically and hence they are assumed not to exist. How these concepts should be classified, that is, what kind of taxonomy should possibly be built upon this conceptual field, has been determined by the construction of the frame. For example, the five subcategories of "celestial body" in 18th century astronomy, that is, star, planet, satellite, returning comet, and non-returning comet, are simply some possible combinations of attribute values defined by the frame (Fig. 5).There is a direct correspondence between Kuhn's account in terms of taxonomies and an account in terms of frames. On the one hand, being part of the same taxonomy

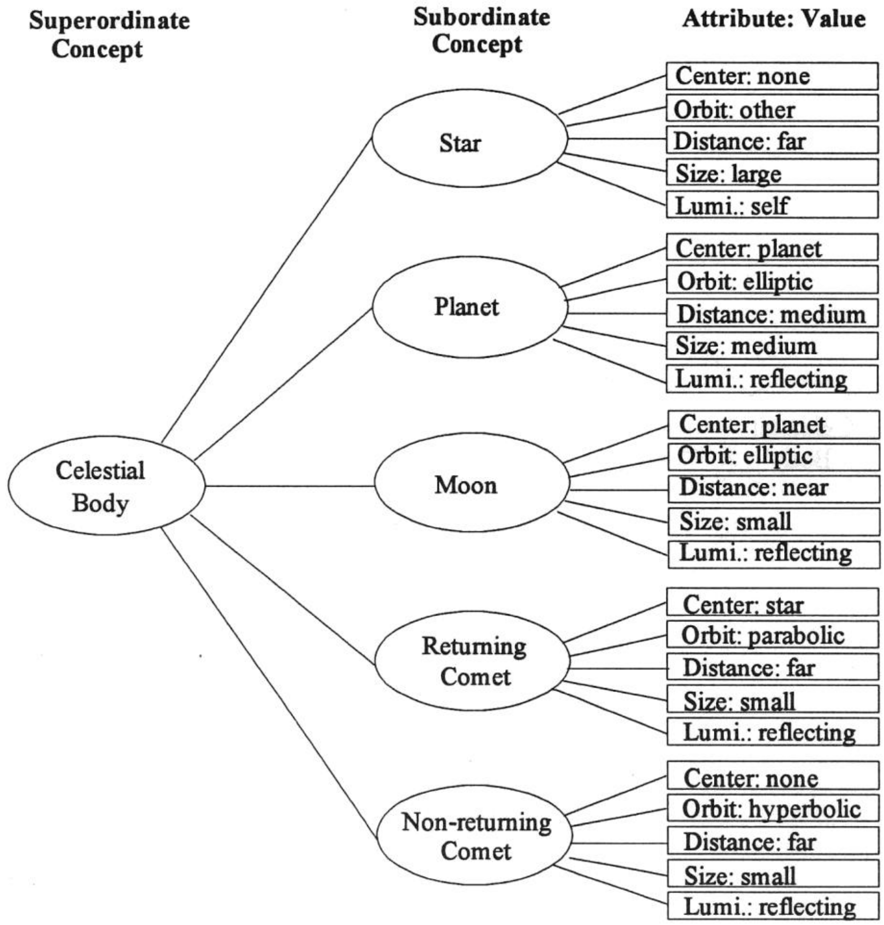

FIG. 5. Partial taxonomy for "celestial body", c. 1700.

means sharing the same frame for a superordinate concept. Also, this superordinate frame functions as a concept generating mechanism for the subordinate concepts. On the other hand, differences in taxonomy reflect differences in frame and, more importantly, differences in concept-generation mechanisms, which produce cognitive barriers for mutual communication. Thus, Kuhn's taxonomic refinement of his account of scientific revolutions can be readily understood as a special case of the more general of frame structures. This has immediate consequences for our understanding of the origins and status of incommensurability.

Kuhn's claims about incommensurability, especially in his latest work, appear as special cases of general features of Barsalou's dynamic frames. Let us briefly examine the correspondences between the two accounts. First and most obviously, any taxonomy defines the structural invariants of a frame for its superordinate concept, as this serves as a concept generating mechanism for its subordinates [6]. As frames are the vehicle for our knowledge of concepts, changing a frame changes the concept. The most obvious sort of change is change of structural invariants. Hence, the taxonomic changes now indicated by Kuhn as the key feature of revolutionary change in science, correspond to changes in the structural invariants of a frame, and hence change in the subconcept generating mechanism inherent in a superordinate concept somewhere in one of Kuhn's taxonomies.

Changes in structural invariants will correlate with changes in the attributes distributed across various values and hence in the membership of various similarity classes, but the latter may not in itself create incommensurability. Looking at the partial frame for "celestial body" (Fig. 4) circa. 1700, we see that the similarity classes "star", "planet", "comet" and "satellite" may be distinguished by similarity and difference among the features identified in the frame (Fig. 5). The difference in the membership of these classes before Copernicus, and after (say) Newton, is striking. But incommensurability is generated here by the appearance (and disappearance) of entire attributes [7]. Before Kepler, astronomical theories were concerned only to predict the angular position of a planet -- no attempt was made to calculate what we would now call the orbit as a continuous path through space. Kepler was actually the first astronomer to attach physical significance to this path, and at the same time calculate what an "orbital path" would look like for a planet in Ptolemaic astronomy (Kepler 1609, 4; cf. Barker and Goldstein 1994, Fig. 4.). Hence the top two attributes in Fig. 4 simply do not appear in pre-Copernican frames for "celestial body". The frames for "celestial body" before Copernicus and after Newton therefore differ in structural invariants. There is a further discontinuity in the superordinate category of "natural object". Before Copernicus, this category divided into mutually exclusive terrestrial and celestial subclasses with opposite features: celestial bodies were unchanging and moved naturally in circles, terrestrial bodies were changeable and moved naturally in straight lines. No such bifurcation occurs in the category of "natural objects" after Newton. Hence the kind hierarchy for "natural object" before Copernicus and after Newton are not isomorphic and neither are the corresponding frames [8].

6. **Conclusion**

The main conclusion we wish to present is that Kuhn's account of concepts is massively supported by empirical work in cognitive psychology. The fundamental point on which Kuhn differs from most philosophers -- the rejection of the traditional view that concepts can be defined by necessary and sufficient conditions, is no longer a matter of serious dispute among psychologists. They agree with Kuhn, and not with the majority view in contemporary philosophy. As might be expected, the accounts psychologists have developed to capture the nuances of empirical data on human concepts -- for example the dynamic frame notation developed by Barsalou -- contain additional details that correspond to features of Kuhn's account, lending further support to it. Kuhn's account may be independently supported from two major research areas in psychology and cognitive science: the consensus position in psychological research on categories and concepts, and perhaps the most attractive cognitive model of concepts, the frame account.

In future work we hope to present and criticize cognitive models of incommensurability based on feature lists and frames, arguing the superiority of the latter. However, the congruences we have sketched between an account of concepts as dynamic frames and Kuhn's account already permits us to draw an additional conclusion. For many years philosophers of science have viewed incommensurability as a liability of any account of science. It should be apparent from what we have already said that the resources needed to generate incommensurability correspond to features that must appear in any account of concepts capable of accommodating empirical research on graded structure, or the additional features of concepts represented by frames. Any account that lacked these resources would be incapable of accommodating human concepts as they are revealed by research in psychology and cognitive science. Far from incommensurability being a liability, it should be regarded as a major objection to any naturalistic account of science if it does not allow for incommensurability between concepts.

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Notes

1. Although the importance of the connection between Kuhn's work and cognitive science has been pointed out by Barker (1994) and Nersessian (1994b), almost no work has appeared on the subject, with the exception of two brief papers by Gibson (1984) and Lachman (1985). Gibson articulates Kuhn's position using the concept of a 'schema' (popularized in AI by the work of Schank). Lachman cites Smith and Cole's (1981) evaluation that schemata could not (at that time) provide a viable account of categories and concepts. Inter alia we will discuss a version of frame theory that is a descendant of the schema theories criticized by Lachman, and which overcomes the difficulties raised by Smith and Cole. Indeed, this version of frame theory is presented by Barsalou as the best account of categories and concepts now available (Barsalou 1992a).
2. Early statements often refer to this structure as the grouping of instances around a prototype. However, during the 1980s prototype theory developed certain technical features that may be problematic and need not concern us here. We will use the more recent term 'graded structure' to designate this phenomenon.
3. The account that follows is adapted directly from Barsalou 1992.
4. Recently Barsalou further grounds frames in perception, suggesting that frame-based perceptual symbols are the foundation of concept representation (Barsalou, 1993b & 1993c).
5. A slightly different, but compatible account has been advanced by Churchland (Churchland 1989, esp. Ch.'s 9-11). His account is based on insights drawn from research in neural nets. Supervised learning in neural nets is very similar to the concept learning procedure described by Kuhn. During the learning process in a neural net the abstract space represented by the network is partitioned into a number of subvolumes, each representing one of the concepts to be learned. The center of each subvolume represents the prototype of the corresponding category. According to this model, once a concept has been learned, recognition of new instances proceeds by registering similarity to one prototype rather than others. Like the frame model we describe, this model too shows the

flexibility required by Kuhn's model: not all possible features of an object need be specified in order to classify the object, while unspecified features will be ascribed values based on the prototype of the selected category.

6. Indeed, conversely, it may be the case that all frames are at least potentially taxonomies - although not necessarily very compact or economical taxonomies.
7. The appearance of new attributes in a frame does not necessarily lead to incommensurability. We have already suggested that individuals may successfully identify the same equivalence classes by different relations of similarity and difference. Should two such individuals compare notes, they might both add several nodes to their frames. It is therefore an important feature of the Copernican revolution that objects were redistributed among the equivalence classes 'planet', 'satellite', etc., while also the structural invariants changed. From Kuhn's viewpoint, as relations of similarity and difference constitute equivalence classes, one ought to say that redistribution of objects among classes (or, more properly, reconstitution of equivalence classes) brings about change in taxonomies.
8. There is much more to say about incommensurability. In the present paper we confine ourselves to showing that frames possess the resources required to capture the combinations of similarity-difference relations that are basic to Kuhn's mature account (see especially fig. 3 and text), and that frames provide a natural way of representing the changes in taxonomic structure that appear in Kuhn's latest account. In future work we hope to review the assets and liabilities of prototype, feature list, and frame based models of incommensurability, and to discuss their application to historical cases in greater detail. For an initial orientation see Chen (1990, 1994).

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