# Nomic Concepts, Frames, and Conceptual Change

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## 1. Thomas Kuhn and Cognitive Science

*1.1. Kuhn and Cognitive Science in the Past.* Thomas Kuhn's *The Structure of Scientific Revolutions* was published at the beginning of what has come to be known as "the cognitive revolution." With hindsight one can construct significant parallels between the problems of knowledge, perception, and learning with which Kuhn and cognitive scientists were grappling and between the accounts developed by each. However, by and large Kuhn never utilized the research in cognitive science—especially in cognitive psychology—that we believe would have furthered his own paradigm. This is puzzling since he did not have the traditional philosophical aversion to "psychologizing" and in fact drew on insights from psychology to support the most radical claims in *Structure*, such as the "Gestalt switch" nature of conceptual change. Indeed, the research program outlined there seems intrinsically historical, philosophical, *and* psychological and Kuhn's work has had considerable influence on research in cognitive science.

We believe the development of the field of cognitive science over the past three decades has led to understandings of human representation, reasoning, and learning that lend support to many of Kuhn's intuitions about scientific practice and provide means for attacking many of the

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unresolved problems posed in Kuhn's research program. Our suspicion is that there are three important reasons why he did not call upon that work in his own post-*Structure* research.

First, his own early attempt in 1969 (Kuhn 1970a, 191f.; 1970c, 274f.; 1974, 310) to devise computational models as tests of his hypotheses about perception and concept learning were unsuccessful. He wanted to develop a computer program that would simulate a non-rule-governed transmission of concepts from one generation to the next. This effort was hampered by the lack of empirical psychological research and by the limitations of programming methods and machines. He never returned to computational modeling nor did he avail himself of the subsequent research on categorization, concept representation, and learning conducted by psychologists.

Second, his intuition was that much of the thinking that takes place in scientific revolutions, normal science, and science learning is not rule-based, but "exemplar-based," so the initial identification of "the computational theory of mind" with rule-based thinking was just the kind of notion from which Kuhn was attempting to move away.

Third, as demonstrated by his retraction of the "Gestalt switch" metaphor of conceptual change, Kuhn wanted to move the level of analysis of scientific practice from that of the individual to that of the scientific community.

However, although the later Kuhn believed it to be a category mistake to apply a psychological mechanism to a community, he continued to believe that scientific practices bear the imprint of both individual cognitive development and the nature of scientific communities. His post-*Structure* focus on issues pertaining to the scientific "lexicon," specifically how the language of a scientific community is acquired and how language change relates to incommensurability, reflects his desire to figure both into an account of conceptual change.

*1.2. Kuhn's New Distinction.* The problem of the nature of concept representation and its relation to conceptual change has been central to Kuhn's research program. In earlier work (Nersessian 1984, 1985; Andersen et al. 1996; Chen et al. 1998; Nersessian and Andersen 1997) we have demonstrated how research on categorization and concept representation in cognitive science can be brought to bear on Kuhn's problem. In this presentation we want to focus on a distinction between kinds of scientific concepts that Kuhn made in one of his last papers. There Kuhn introduced a distinction between *normic* concepts and *nomic* concepts. Normic concepts are those which in their use allow for exceptions in the generalizations usually satisfied by the referents, such as 'liquid', 'gas', and 'solid' where generalization such as "liquids expand when heated" may sometimes fail, for example for water between 0 and 4 degrees centigrade (Kuhn

1993, 316). Nomic concepts, on the contrary, are concepts for which the generalizations are exceptionless laws of nature, such as 'force' which is defined by Newton's three laws of motion. (Kuhn 1993, 316ff.).

Throughout his work on conceptual change Kuhn adopted the traditional philosophical position that a scientific conceptual structure is a language. However, his analysis of the notion of incommensurability as untranslatability, led him to focus on the processes through which languages are learned to form insights into concept representation and the relation of earlier to later conceptual structures, rather than on analyses of the structures themselves. We see this as central to his attempt to develop a position informed both by the practices of scientific communities and by considerations of individual cognition.

For most of his insights he relied on an intuitive example of a child learning the concepts 'duck', 'goose', and 'swan' to illustrate his approach. Using this example, Kuhn developed a detailed account of the process by which everyday concepts are transmitted from one generation to the next (Kuhn 1974, 309ff.) and then he simply postulated an analogy between everyday concepts and scientific concepts. So, based on the detailed example of 'waterfowl', he claimed that "the same technique, if in a less pure form, is essential to the more abstract sciences as well. I have already argued that assimilating solutions to such problems as the inclined plane and the conical pendulum is part of learning what Newtonian physics is. Only after a number of such problems have been assimilated, can a student or a professional proceed to identify other Newtonian problems for himself. The assimilation of examples is, furthermore, part of what enables him to isolate the forces, masses, and constraints within a new problem and to write down a formalism suitable for its solution" (Kuhn 1974, 313).

We too believe that ordinary and scientific concept representation and learning lie on a continuum. But this does not rule out the possibility of significant differences, and in most of his work Kuhn overlooked an important potential difference between ordinary and scientific concepts. With concepts like 'duck', 'goose', and 'swan', their instances can be ostended individually and many similarities and dissimilarities between them discovered through that process. Such a learning procedure would at best apply to a limited range of scientific concepts. A scientific concept such as 'planet' can be ostended individually and in contrast to concepts like 'star' and 'satellite', but concepts involved in scientific laws usually cannot be ostended individually. Instances of the concept 'mass', e.g., are not pointed out in isolation to reveal similarity between the instances, and no contrasting concepts exist whose instances could reveal how the instances of 'mass' differ from other concepts. It is this difference which Kuhn's late normic/nomic distinction was intended to catch.

It would appear that in distinguishing between 'nomic' and 'normic' concepts Kuhn saw the need to introduce a distinction between similarity class (or family resemblance) concepts and non-similarity class concepts, viz., concepts explicitly defined by scientific laws. This is highly remarkable, since it has been one of Kuhn's key points since the 1970 postscript to *Structure* that all concepts, including scientific concepts, are based on similarity rather than definition.

However, we argue in the following, first, that the new distinction is a result of problems inherent in Kuhn's previous position which only remained unnoticed due to the very limited range of examples Kuhn drew upon. Second, we argue that family resemblance is the basis on which both normic and nomic concepts build, but that in the case of nomic concepts the family resemblances are among problem situations and not features of individual concepts. Finally, we show that our frame-based account reveals insights into significant problems associated with conceptual change and the incommensurability.

## 2. The Development of Kuhn's Theory of Concepts

*2.1. The Role of Exemplars.* Kuhn's focus on the role of exemplary problem solutions in scientific practice and pedagogy led his work to take a Wittgensteinian direction from the outset. In *Structure* Kuhn suggested that exemplary research problems and their solutions might very well be related in the same way as Wittgenstein had described for the instances of everyday concepts like 'chair', 'leaf', or 'game', that is, by a network of overlapping and crisscrossing resemblances (Kuhn 1970, 44ff.). As Kuhn stated, what research problems "have in common is not that they satisfy some explicit or even some fully discoverable set of rules and assumptions that gives the tradition its character and its hold upon the scientific mind. Instead, they may relate by resemblance and by modeling to one or another part of the scientific corpus which the community in question already recognized among its established achievements" (Kuhn 1970a, 45).

*2.2. The Initial Rejection of Definitions.* Kuhn recognized that his claim was "entirely theoretical: paradigms *could* determine normal science without the intervention of discoverable rules" (Kuhn 1970a, 46; italics in original). However, in support of this claim he noted that "scientists . . . never learn concepts, laws, and theories in the abstract and by themselves, but through applications" (1970a, 46), and pointed to "the severe difficulty of discovering the rules that have guided particular normal-science traditions" (1970a, 46). So far this is only a claim that in the actual scientific practice, concepts are not defined, but not an argument that concepts cannot *in principle* be defined. Later Kuhn did make this much stronger claim, arguing that although it may be possible to reconstruct definitions of scientific concepts which would all "be equivalent with respect to the community's past practice, they need not be equivalent when applied to the very next problem faced by the discipline" (Kuhn 1974, 303; see also Hoyningen-Huene 1993, Ch. 3.6.f.).

His argument for this claim is based on observations that use of similarity and dissimilarity relations, allows different members of the language community to identify referents and non-referents of objects by different criteria. Thus, individual differences between members of the same language community may exist that are not apparent in the usual linguistic practice. This masking of differences is possible as long as there is an empirical correlation between the different characteristics used. However, were an *exception* to the empirical correlation to appear, speakers basing their relations of similarity and dissimilarity on different characteristics would no longer use all concepts in the same way. Thus, the difference that exists only in latent form before the exception appeared would come to notice for the first time. Thus the relations of similarity and dissimilarity not only establish the unequivocal use of concepts in consensus situations, but also at the same time provide the resources to explain divergence in concept use and the appearance of dissensus. So, although it may be possible to reconstruct definitions of scientific concepts which adequately capture their use at a specific time, such reconstructions are not able to deal with a future development of divergence.

*2.3. The Basic/Theoretical Distinction and the Nomic/Normic Distinction.* Although introduced only in his later writings, the normic/nomic distinction bears resemblance to a previous distinction in Kuhn's work between 'basic' and 'theoretical' concepts, which he saw as different from, but related to the classical distinction between theoretical and observational terms. From the outset Kuhn rejected the observational/theoretical distinction of logical positivism. However, at the same time he maintained throughout his work a distinction between concepts that "are ordinarily applied by direct inspection" and concepts for which "laws and theories also enter into the establishment of reference" (Kuhn 1979, 412).

This distinction has been reconstructed by Hoyningen-Huene as that between concepts learned without or with the help of laws or theories (Hoyningen-Huene 1993, Ch. 3.6). According to this reconstruction, what Kuhn called "basic" concepts or concepts "applied by direct inspection" and Hoyningen-Huene calls "concepts learned without the use of laws and theories" are learned through ostension. In this process, not only are the instances of the concept to be learned ostended, but also instances of other concepts for which it might otherwise be mistaken. The language learner then has to discover the characteristics with respect to which instances of one concept are similar, and characteristics with respect to which instances of different concepts are dissimilar. Thus, basic concepts build on similarity (or, in Wittgensteinian terms, family resemblance) and are acquired together in contrast sets.

The other kind of concepts—"theoretical" concepts or concepts "learned with the use of laws and theories"—are learned by having problem situations to which a given law applies pointed out rather than individual objects. For example, problem situations to which Newton's second law apply may be the simple pendulum, free fall, or harmonic oscillators. What Kuhn claimed is that such *problem situations* form similarity classes much the same way as *instances* of 'basic' concepts do, thus downplaying the difference between 'basic' and 'theoretical' concepts.

However, treating both kinds of concepts as similarity class concepts gives rise to a fundamental problem. Whereas for basic terms, in order to learn the concept, several instances of the concept are ostended, for theoretical terms what is pointed out are not instances of *individual* concepts but complex problem situations to which a given law applies and which involve the simultaneous use of *several* concepts. For example, in the former case instances of contrasting concepts like 'goose', 'swan', and 'duck' are ostended individually, while in the latter case what is pointed out are instances of the application of a natural law like, for example, Newton's second law, F = ma, in which the concepts 'force', 'mass', and 'acceleration' are simultaneously involved.

In introducing the later, parallel distinction between normic and nomic concepts, Kuhn again referred to a difference in the way the two kinds of terms are learned (Kuhn 1993, 317). Normic concepts are learned the way Kuhn always claimed basic concepts to be learned, viz., in contrast sets by identifying similarities between instances of the same concept and dissimilarities to instances of contrasting concepts. Hence, normic concepts are learned by ostension of individual objects in a process in which each individual object is ascribed to one of the concepts in a contrast set and simultaneously not ascribed to the other concepts in the set. Nomic concepts, on the contrary, are not learned in contrast sets, since, as we pointed out earlier, instances of a concept like 'mass' cannot be pointed out in isolation to reveal similarity between instances of the same concept and differences to instances of contrasting concepts. Instead, "they are learned from *situations in which they occur together*, situations exemplifying laws of nature" (Kuhn 1993, 317; italics added). In both Kuhn's earlier account of 'theoretical' concepts and his introduction of the notion of 'nomic' concepts, he focused on the family resemblance between the problem situations to which a given law could be applied, but said nothing about how the referents of the *individual* concepts such as 'force', 'mass', and 'acceleration' involved in such non-contrasting relations as Newton's second law could identified.

We have serious doubts as to whether there are any scientific concepts that can be learned "without the use of laws and theories," and whether the normic/nomic distinction is tenable as a clear-cut distinction at all. However, we do think that Kuhn, in the end, came to see some significant problems for his initial account of scientific concepts: the entwinement of scientific concepts with theory, and their co-occurrence in problem situations. Problems similar to those with which Kuhn was struggling will be familiar to cognitive scientists who have worked on categorization and concept representation, namely: although many concepts exhibit a family resemblance structure, certain kinds of concepts do seem to have a definition-like "core"; and many ordinary concepts appear intertwined with theories, that is, they are learned together with intuitive theoretical understandings. We will not attempt to connect Kuhn's work with these cognitive science analyses here, but clearly what he called nomic concepts exhibit both of these features of ordinary concepts. Making progress on accounting for these features of scientific concepts is valuable whether or not Kuhn's distinction is tenable.

**3. Nomic Concepts, Problem Situations, and Frames.** As discussed in the previous section, when Kuhn introduced the notion of nomic concepts, he stressed only the family resemblance between the *problem situations* to which a given law can be applied, but not how the referents of the *individual concepts* such as 'force', 'mass', and 'acceleration' involved in such non-contrasting relations as Newton's second law, $F = ma$, could be identified. Thus we interpret Kuhn to mean that in this case the similarity view rightly applies to the *problem situations*: situations cannot be defined but exhibit a set of family resemblances. We propose that representation of the nomic concepts requires two layers: one that represents the family resemblances among the *problem situations* in which these concepts participate (the problem Kuhn attempted to address) and one that represents the salient features of individual concepts participating in these situations (the problem Kuhn did not address).

*3.1. A Frame Representation of Normic Concepts.* Recent work by Andersen and others (Andersen et al. 1996, Chen et al. 1998) has demonstrated the fertility of the dynamic frames approach to concept representation developed by Lawrence Barsalou (1992) for the representation of normic concepts and addressing issues about conceptual change. We believe that analysis can be extended to represent the similarity class of problem situations for nomic concepts. The dynamic frame representation Barsalou developed for representing ordinary concepts captures the fundamental aspects of the family resemblance account of normic concepts. Figure 1 shows how the frame representation can be used for ordinary and for normic concepts. Here we claim that for nomic concepts,

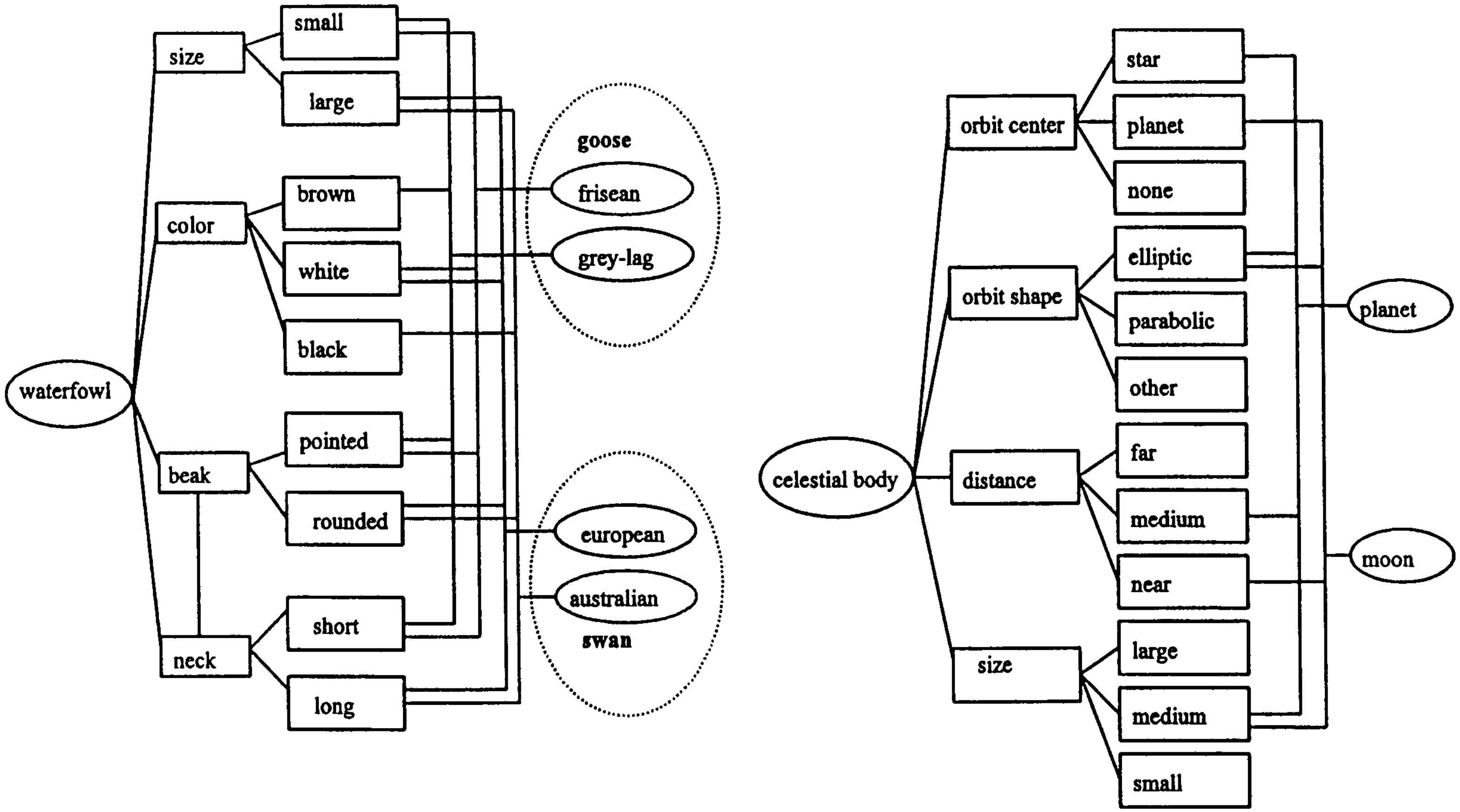

Figure 1. Partial frames for normic concepts such as 'goose', 'swan', 'planet', or 'moon'.

the dynamic frame form of representation can be extended to capture the similarity class among problem situations.

*3.2. A Frame Representation of Problem Situations.* Consider, for example, a variety of problem situations pertaining to electrostatic action, as shown in Figure 2. These problem situations all involve the attributes **charge distribution, electric field, electric action,** and **electrostatic potential.** The attributes of the problem situation can take different values; for example, **charge distribution** takes—among others—the different values **point charge, line charge,** and **surface charge**. Figure 3 is our extension of the frame representation to nomic concepts. On this representation of 'electrostatic action', the different forms of the electrostatic equations are associated with different instantiations of the frame, that is, with different patterns of values of the attributes. For example, the various forms of Gauss's equation are associated with instantiating specific values of **charge distributions** and **electric field**. Thus, instantiating the value **point charge** (**charge distribution**) and the value **spherical** (**electric field**) is associated with the equation $\mathbf{E} = Q/(4\pi\epsilon_0 r^2)\mathbf{a}_r$. Likewise, instantiating the values **line charge** and **radial** is associated with the equation $\mathbf{E} = \rho/(2\pi\epsilon_0 r^2)\mathbf{a}_r$. Here, the various situations to which the equation applies as well as the specific forms of the equation are related by family resemblance, while the exceptionless generalization is a relation that holds between the individual attributes in the situation, here the **charge distribution** and the **electric field.**

Likewise, another instantiation pattern is associated with the similarity class of problem situations that can be described by Coulomb's law. The instantiation of the value **point charge** and the **electric action** is associated with the equation $\mathbf{F} = q_1q_2/(4\pi\epsilon_0)\mathbf{r}_{12}^{-2}$, while that of **surface charge** and the **electric action** is associated with the equation $\mathbf{F} = q/(4\pi\epsilon_0)\int_S(\mathbf{r}-\mathbf{r}')/|\mathbf{r}-\mathbf{r}|^3\sigma(\mathbf{r}')da'$. Again, the various situations to which the equation applies as well as the specific forms of the equation are related by family resemblance, while the exceptionless generalization is a relation which holds between the individual attributes in the situation, here the **charge distribution** and the **electric action**.

*3.3. The Problem of Individuating Nomic Concepts.* Kuhn also claimed that individual nomic concepts are learned in the problem situations, such as those for electrostatic action. As it stands, the frame representation for nomic concepts only individuates the problem situations in which concepts participate, but not the individual concepts. An additional layer of representation is required to individuate concepts. Although it predates Kuhn's introduction of the normic/nomic distinction, Nersessian (1984) presented an analysis that we think can be brought to bear on this issue. Two results of her research on the historical formation of the electromagthe dynamic frame form of representation can be extended to capture the similarity class among problem situations.

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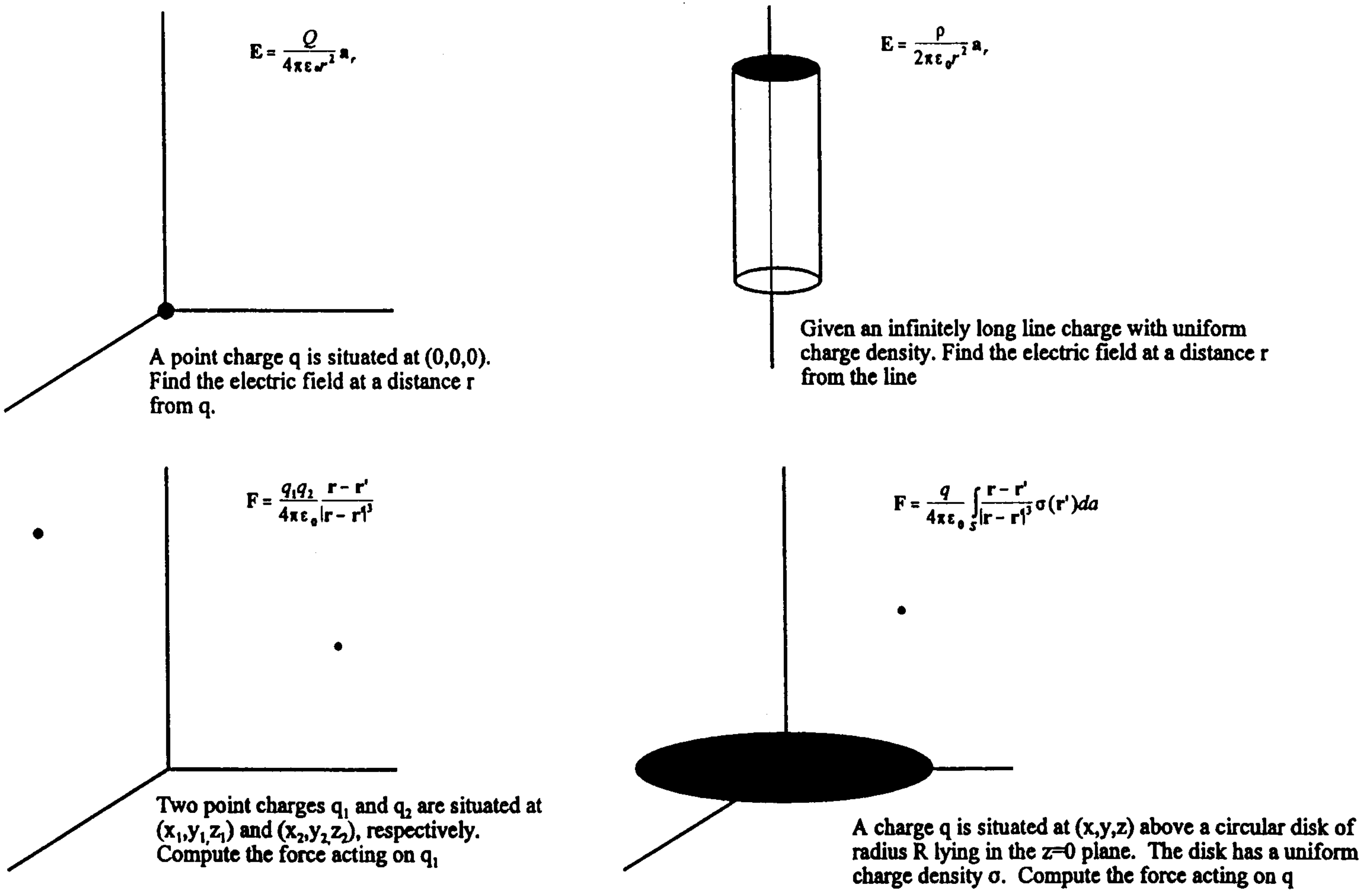

$$\mathbf{E} = \frac{Q}{4\pi\varepsilon_0 r^2}\mathbf{a}_r$$

A point charge q is situated at (0,0,0). Find the electric field at a distance r from q.

$$\mathbf{E} = \frac{\rho}{2\pi\varepsilon_0 r^2}\mathbf{a}_r$$

Given an infinitely long line charge with uniform charge density. Find the electric field at a distance r from the line

$$\mathbf{F} = \frac{q_1 q_2}{4\pi\varepsilon_0}\frac{\mathbf{r}-\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|^3}$$

Two point charges $q_1$ and $q_2$ are situated at $(x_1,y_1,z_1)$ and $(x_2,y_2,z_2)$, respectively. Compute the force acting on $q_1$

$$\mathbf{F} = \frac{q}{4\pi\varepsilon_0}\int_S \frac{\mathbf{r}-\mathbf{r}'}{|\mathbf{r}-\mathbf{r}'|^3}\sigma(\mathbf{r}')\,da$$

A charge q is situated at (x,y,z) above a circular disk of radius R lying in the z=0 plane. The disk has a uniform charge density σ. Compute the force acting on q

Figure 2. Electrostatic problem situations.

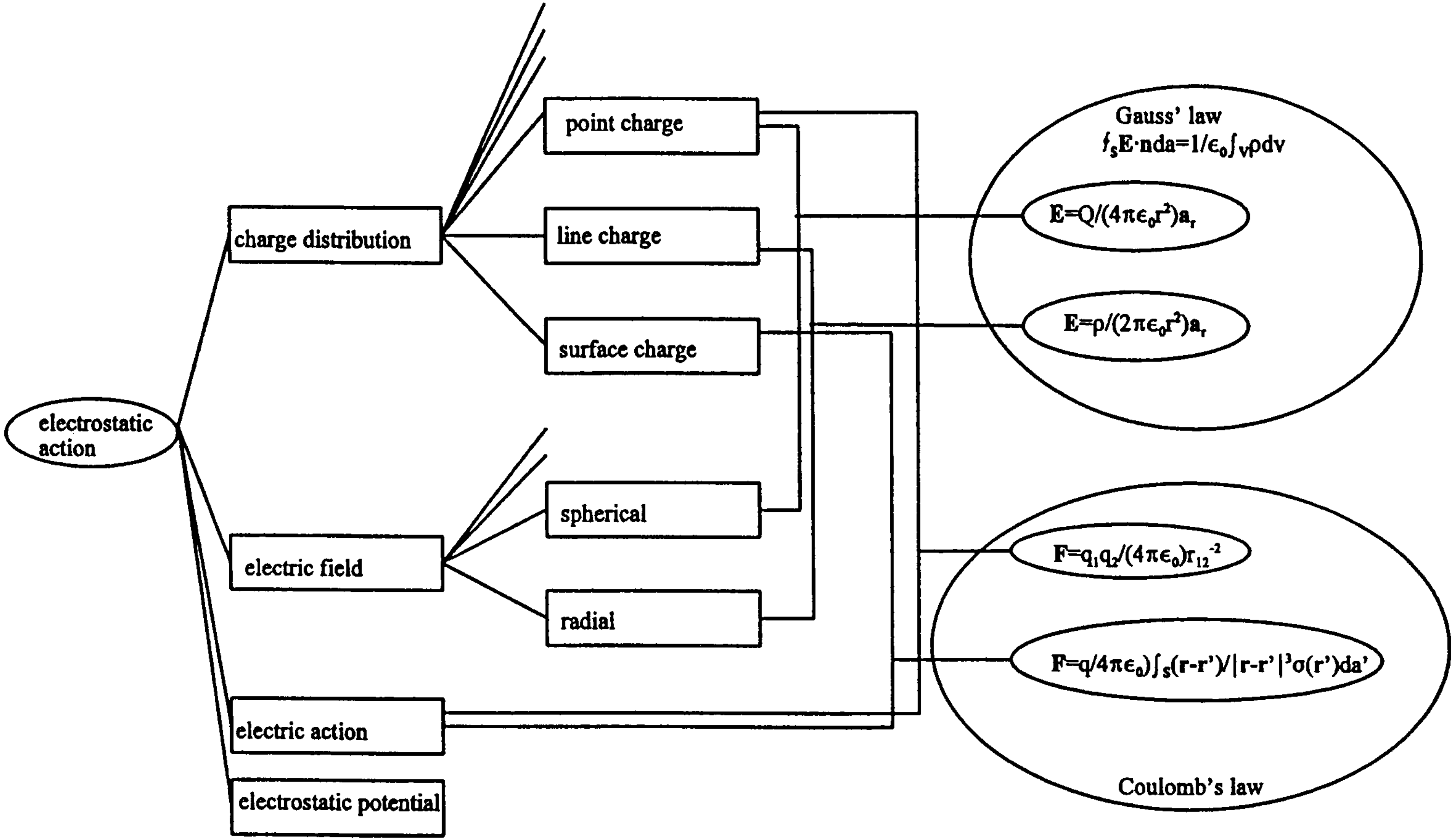

Figure 3. Partial frame form nomic concept 'electrostatic action'.

netic field concept were that, first, there is no way of extricating the representation of 'electromagnetic field' from the problem situations in which it participates and that, second , the various instances of the field concept in the theories of Faraday, Maxwell, Lorentz, and Einstein exhibit a family resemblance-like structure. She argued that these kinds of scientific concepts—which we are now calling "nomic" following Kuhn—could be represented by a "meaning schema." This is a frame-like structure in which a scientific concept is represented by four components central to its descriptive and explanatory function: ontological status, function, mathematical structure, and causal power. Figure 4 links the meaning schema for 'electromagnetic field' to partial frame for the problem situations pertaining to electrostatic action. The *causal power* of a concept includes its effects, i.e., it marks out the problem situations in which the concept comes into use in order to explain the situation. Hence, this component of the meaning schema can be linked to the frame representing a similarity class of problem situations. Likewise, the *mathematical structure* corresponds to the exceptionless laws associated with this similarity class of problem situations. The additional components of the meaning schema—'function' and 'ontological status'—are the components which serve to distinguish individual concepts within the complex situation.

The *function* of a concept marks out a specific part of the explanation of a problem situation and clarifies its explanatory role. For example, for the two kinds of problem situations dealing with electrostatic action introduced above, situations dealing with the electric field arising from a charge distribution (i.e., *causal power*) and described by Gauss equation (i.e., *mathematical structure*: $\oint_S \mathbf{E}\cdot\mathbf{n}da = (1/\epsilon_0)q_i$) or situations dealing with the electric force exerted on a charged body due to the presence of other electric charges (*causal power*) and described by the Coulomb equation (*mathematical structure*: $\mathbf{F}_i = q_i\Sigma(q_j\mathbf{r}_{ij})/(4\pi\epsilon_0 r_{ij}^3)$), the various quantities contained in these equations play different roles in the explanation of why a given problem situation develops as it does. For example, the electric field intensity (E) transmits the electric action (F) that is exerted on a charged body due to the presence of other electric charges (q). To the various functions corresponds an *ontological status*, that is, a belief about what kind of "stuff" is responsible for this particular function. Here charge is a property of a particle (electron) and the electromagnetic field is a state of space.

**4. Nomic Concepts and Conceptual Change.** What we have shown thus far is that even though Kuhn's normic/nomic distinction takes note of the fact that in science many of the concepts have a definitional dimension, nevertheless family resemblance still plays a major role in the way in which both kinds of concepts are learned and can be represented. Further, we

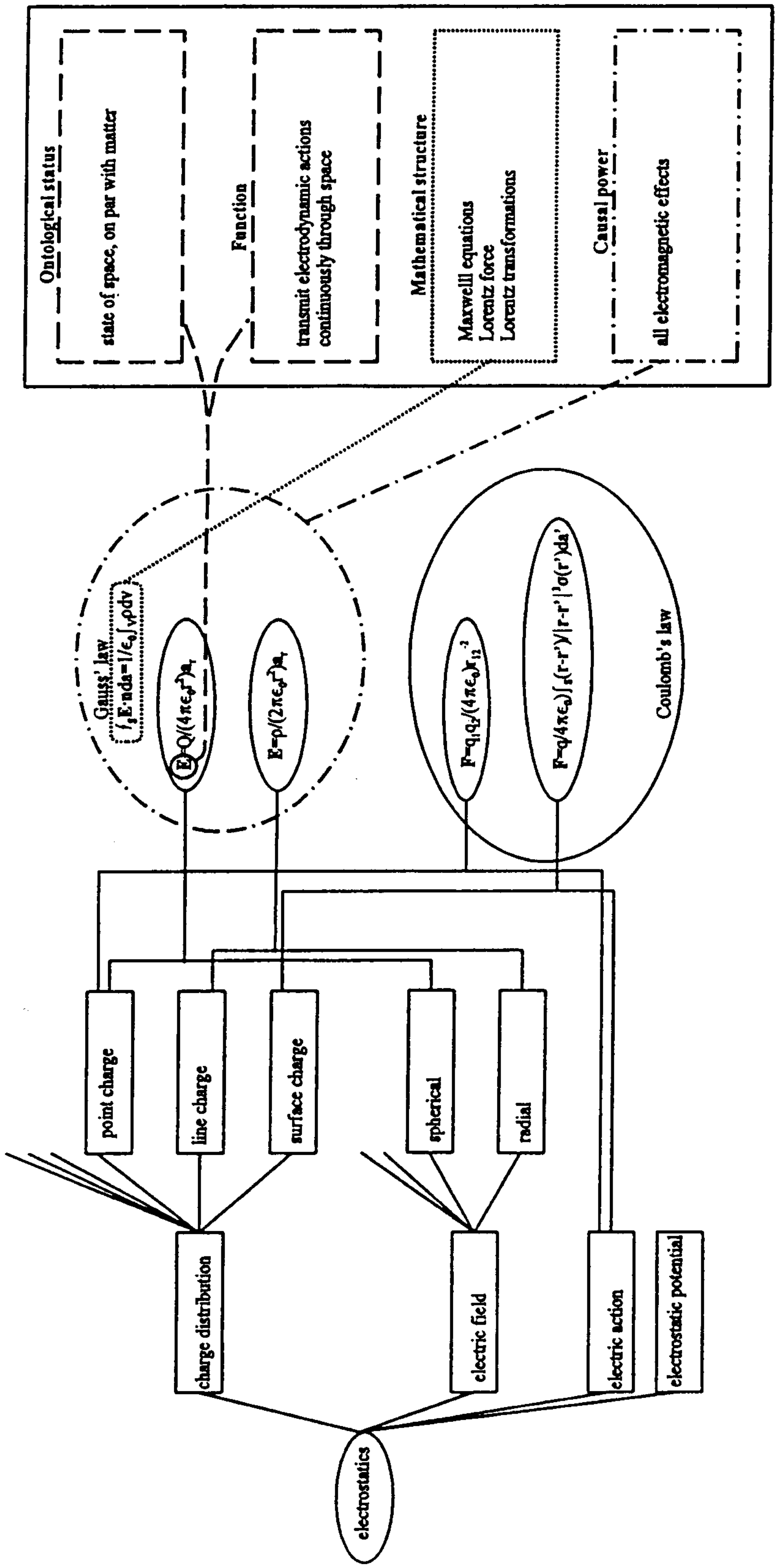

Figure 4. Meaning schema for individuating 'electromagnetic field' in electrostatic problem situations.

have shown that although nomic concepts are learned in complex problem situations it still is possible to distinguish individual concepts as they participate within the various problem situations. In closing we will consider one insight that can be gleaned about the processes of conceptual change from examining these layers of representation.

*4.1. The No-Overlap Condition for Problem Situations.* In previous work on normic concepts, Chen et al. (1998, 20ff.) have argued—with Kuhn—that a similarity class account of concepts implies that contrasting concepts are not allowed to overlap in their extensions. No ducks may also be swans, no planets may also be stars, no radium may also be barium. If contrasting concepts are found to overlap, this will cause dissatisfaction with the current conceptual structure and precipitate conceptual change. Since, as we have argued, complex problem situations form similarity classes, we also claim the same no-overlap condition must hold on the level of situations and hypothesize that such that violations may trigger conceptual change.

As an example of this, consider the following historical case. In his 1905 paper on relativity, Einstein presented a problem that he claimed called Maxwellian electrodynamics into question for him. Electromagnetic induction is produced by motion of a magnet and a conductor relative to one another. However, in Maxwellian electrodynamics, although the resultant electromagnetic induction is the same whether it is the magnet or the conductor that is moving and the other at rest, these are interpreted as two different kinds of problem situations.

According to Maxwellian electrodynamics, the frame representing 'electrodynamic action' (Figure 5a) includes the attributes **conductor**, **magnet**, and **ether**. Both the **conductor** and the **magnet** can take the two different values **moving** and **at rest**, and in both cases the two values are taken relative to the **ether**. Instantiating the value **moving** for the **conductor** and **at rest** for the **magnet** yields a similarity class of problem situations that can be described by the Lorentz force ($\mathbf{F} = q(\mathbf{E}+\mathbf{v}\times\mathbf{B})$) but in which there is no electromotive force ($\oint \mathbf{E}\cdot d\mathbf{l} = 0$). On the contrary, instantiating **at rest** for the **conductor** and **moving** for the **magnet** yields a similarity class of problem situations that can be described by a electromotive force but in which there is no Lorentz force. Hence, the two situations belong to different similarity classes of problem situations that are described by different equations and that call on different ontologies.

However, the two apparently contrasting similarity classes of problem situations are both used to explain exactly the same phenomenon of electromagnetic induction. In both cases a voltage is produced, and the numerical value of the voltage is identical in the two cases. What Einstein understood was that there is a *total overlap* between two similarity classes.

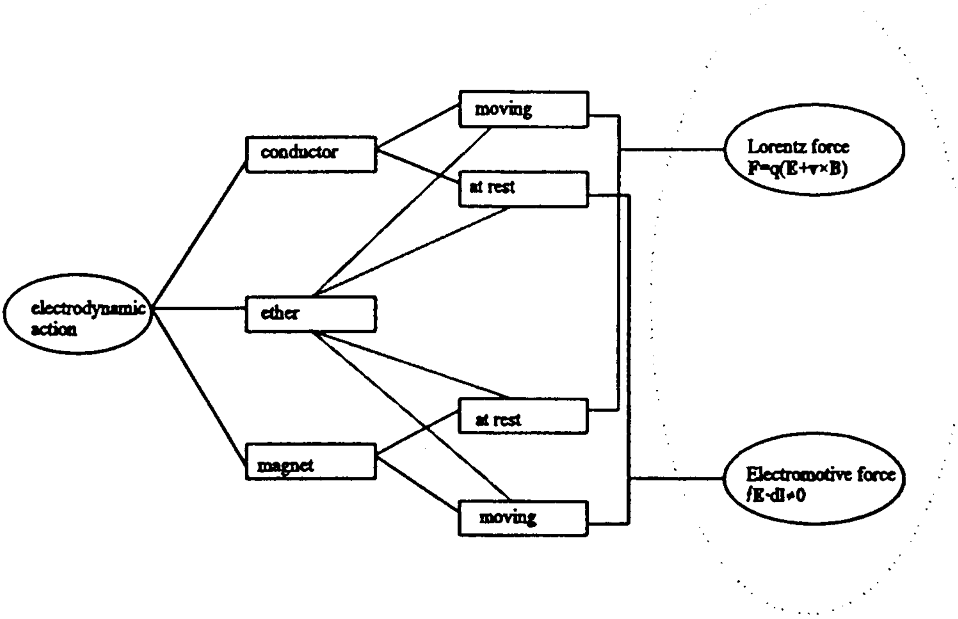

Figure 5a. Partial frame for Maxwellian 'electrodynamic action'.

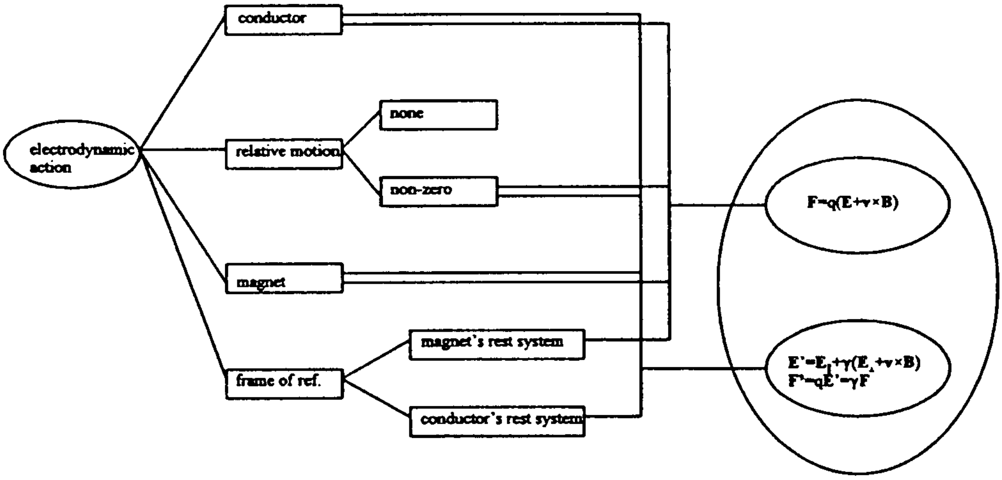

Figure 5b. Partial frame for Einsteinian 'electrodynamic action'.

This is a violation of the no-overlap condition. As we all know, removing this overlap would require that the frame representing the electrodynamic action no longer includes in its problem situations the attribute **ether,** which in the Maxwellian frame served to distinguish the two similarity classes, but has no role in the Einsteinian interpretation (thus Einstein's remark that "the ether is superfluous"). Instead, the Einsteinian frame (Figure 5b) contains the attributes **relative motion** and **frame of reference,** where the former can take the values **none** and **non-zero** and the latter attribute can take the values **magnet's rest system** and **conductor's rest**

**system**. Instantiating **magnet's rest system** together with **magnet, conductor,** and **non-zero relative motion** is associated with a similarity class of problem situation which—in this frame of reference—can be described by the Lorentz force. Instantiating the value **conductor's rest system** together with **magnet, conductor,** and **non-zero relative motion** as associated with a transformed electric field which leads to the Lorentz force in its transformed form. In the Einsteinian frame the two problem situations now belong to the same similarity class of problem situations that can be described by the same equations and transformation rules and that employ the same ontology of electric and magnetic fields.

Changing the frame representing electrodynamic action to remove an overlap between two similarity classes of problem situations also implies potential changes in the individual concepts involved in the problem situations. We can represent these changes occurred by connecting the problem situation frame to full meaning schema representing the historical development (Figure 6). For example, although the causal power of the concept 'electromagnetic field' remains the same, the mathematical structure (in Kuhn's terminology the exceptionless laws associated with the problem situations) is changed to the relativistic form. Correspondingly, the concept of 'ether' looses its function and ontological status and thus disappears. But, despite major conceptual change, there is still significant continuity between the Maxwellian and the Einsteinian concepts of field.

**5. Conclusion.** With Kuhn we believe that understanding ordinary concept formation, representation, and learning does have implications for understanding conceptual change in science. But we also believe that Kuhn's progress on this problem was impeded by his following the traditional philosophical approach of relying on his own intuitions about these issues. Instead, we hope to have demonstrated that progress on seemingly intractable problems can be made by combining philosophical and historical analysis with cognitive science research. We are not advocating that research in cognitive science be adopted uncritically and applied wholesale to understanding science, but reflexively in what we have called "cognitive-historical" analyses. Such analyses require a deep understanding of the history of science and of problems pertaining to the nature and development of scientific knowledge—both of which Kuhn certainly possessed.

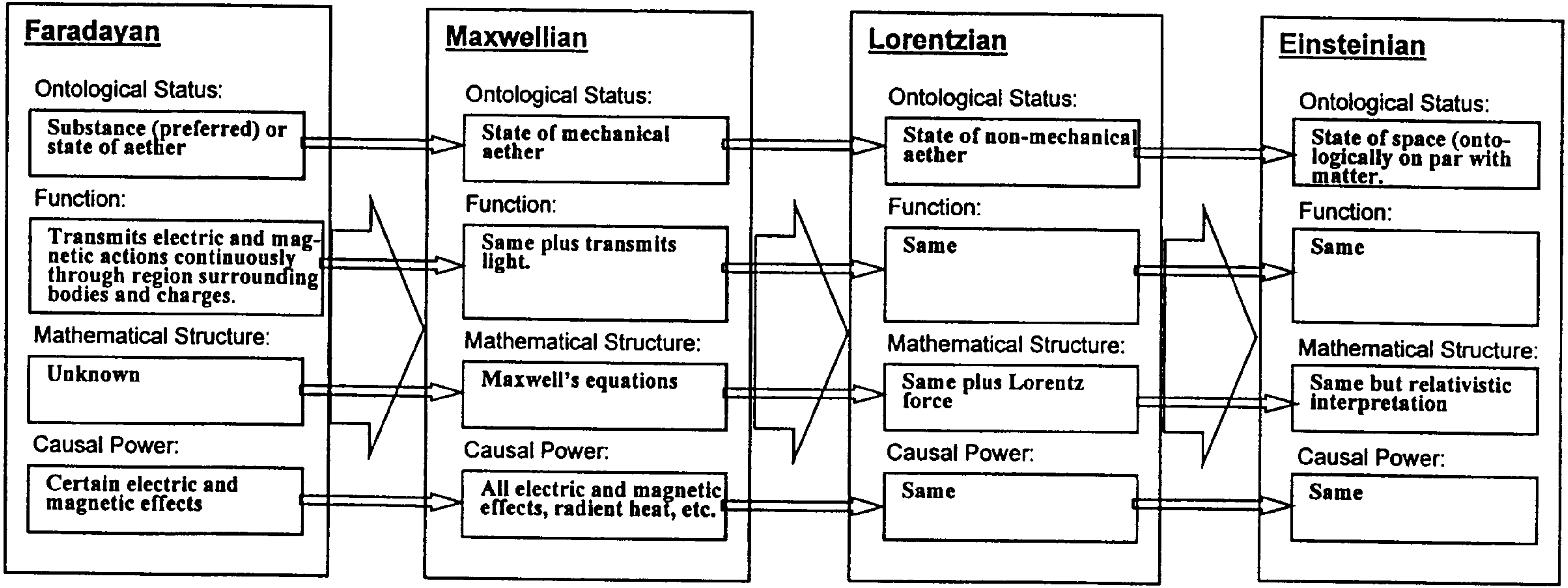

Figure 6. Meaning schema for historical instances of 'electromagnetic field'. (Arrows indicate chain of reasoning connections)

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