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The Object Bias and the Study of Scientific Revolutions: Lessons from Developmental Psychology

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I propose a new perspective on the study of scientific revolutions. This is a transformation from an object-only perspective to an ontological perspective that properly treats objects and processes as distinct kinds. I begin my analysis by identifying an object bias in the study of scientific revolutions, where it takes the form of representing scientific revolutions as changes in classification of physical objects. I further explore the origins of this object bias. Findings from developmental psychology indicate that children cannot distinguish processes from objects until the age of 7, but they have already developed a core system of object knowledge as early as 4 months of age. The persistence of this core system is responsible for the object bias among mature adults, i.e., the tendency to apply knowledge of physical objects to temporal processes. In light of the distinction between physical objects and temporal processes, I redraw the picture of the Copernican revolution. Rather than seeing it as a taxonomic shift from a geocentric to a heliocentric cosmology, we should understand it as a transformation from a conceptual system that was built around an object concept to one that was built around a process concept.

Keywords: Copernican Revolution; Developmental Psychology; Object Bias; Object Concepts; Philosophy of Science; Process Concepts; Scientific Revolutions; Taxonomic Shifts

1. Distinctions Between Objects and Processes

It is common knowledge that the world that we live in consists not only in a variety of physical objects, such as rocks, swans, and cars, but also in a variety of temporal processes, such as waves, engine cycles, and meetings.[1] It is also common knowledge

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that physical objects and temporal processes are two different kinds of entities. Evidence to the distinction between these two kinds of entities first comes from our language: we consciously apply different types of predicates to describe different kinds of entities. In English, we use one type of predicate to modify nouns referring to physical objects, and a different type of predicate to modify nouns referring to temporal processes. For example, we always use object predicates such as 'white' and 'green' to modify 'swan'. The first noun–predicate combination would be a true statement while the second would not, but both are meaningful in the sense that we can judge whether they are true or false. Similarly, we always use temporal predicates such as 'one-hour long' or 'one-second long' to modify 'meeting'. However, we never apply an object predicate to modify a temporal noun, nor the other way around. It is meaningless to use 'white' to modify 'meeting', or to use 'one-hour long' to describe 'swan', because these noun–predicate combinations are semantically anomalous in the sense that we cannot judge whether they are true or false.

Our knowledge of sensible noun–predicate combinations has its ontological root. Object and temporal nouns require different types of predicates because physical objects and temporal processes have distinct ontological characters. We can identify the ontological differences between physical objects and temporal processes through examining their relations with such metaphysical categories as MATTER, SPACE and TIME.

Physical objects are three-dimensional material occupants of space for a time. Since physical objects consist of matter of one kind or another, they inherit the basic properties of materials. Thus, a typical physical object, such as a rock, a swan, or a car, has solidity, weight, size, shape, and texture.[2] In addition, physical objects always endure over time. The lives of physical objects cannot be instantaneous—they are temporally permanent, and they exist continuously. Finally, typical (macroscopic) physical objects always occupy space and their occupancy is both unique and exclusive. An object can occupy different positions at different times, but it cannot be at more than one place at a given time. Because objects occupy and compete for space, two objects cannot occupy the same place at the same time, and one particular place cannot be occupied by more than one object at a given time.

Temporal processes are successions of actions or changes taking place over time. They do not consist of matter, and have no shape, texture, or color. Furthermore, temporal processes do not endure over time—they always vary over time after they have taken place. Unlike changes of a physical object that consist in gaining or losing properties, changes of a temporal process are transformations from one phase to another within the process. Finally, temporal processes occur in space but do not occupy space. Unlike a physical object, a temporal process can be at more than one place at a given time—a wave cannot be placed in any exact location at a given time. Because temporal processes do not compete for space, two temporal processes can occupy the same place at the same time—a meeting and a debate can occur in the same space at the same time.[3]

Although we are sensitive to the distinction between physical objects and temporal processes in a cognitive task such as using a predicate to describe a noun, evidence from the cognitive sciences indicates that we are much less responsive to the object–process distinction in other cognitive tasks. We sometimes fail to recognize the differences between these two distinct ontological kinds, and we occasionally even misjudge one kind of entity as the other, calling a temporal process a physical object or the other way around. In theory, the confusion over physical objects and temporal processes can take either direction, but in practice we make more errors in the direction of treating a temporal process as a physical object than treating an object as a process. We tend not to treat the two ontologically distinct kinds equally, and we rely more on our knowledge of physical objects than on that of temporal processes in various cognitive tasks. In other words, we have a preference for physical objects, and we prefer to view temporal processes as physical objects. I call this preference for physical objects the *object bias*. In the following sections, I first identify such an object bias in the study of scientific revolutions, where it takes the form of representing scientific revolutions as changes in classification of physical objects, or, in other words, as taxonomic shifts.

I further explore the origins of this object bias. Findings from developmental psychology indicate that children cannot distinguish processes from objects until the age of 7, but they have already developed a core system of object knowledge as early as 4 months of age. Part of this core system of object knowledge remains intact when infants grow, and it evolves to become commonsense understandings of adults. Because it is effective to account for many phenomena in daily life, adults never completely give up this core system of object knowledge in their commonsense reasoning. They frequently rely on this core system to comprehend complicated phenomena of physics, and consequently encounter profound difficulties. The persistence of this core system—i.e., that tendency to apply knowledge of physical objects to phenomena belonging to other ontological categories such as temporal processes—is responsible for the object bias among mature adults.

Finally, in light of the distinction between objects and processes, I redraw the picture of the Copernican revolution. To account for many recent findings from the history of science, I argue that we must eliminate the object bias and understand this historical episode as a transformation from a conceptual system built around an object concept to one built around a process concept.

2. The Object Bias in Philosophy of Science

2.1. Kuhn's Theory of Kinds

In the study of scientific revolutions, the object bias takes the form of representing conceptual changes in the history of science as transformations of object concepts. More precisely, it takes the form of representing scientific revolutions as changes in classification of physical objects—as taxonomic shifts. We can find a typical example of such an object bias in Kuhn's mature writings.

In *The Structure of Scientific Revolutions*, Kuhn (1970) used a Gestalt analogy to illustrate a critical feature of conceptual changes in science—after a scientific revolution, scientists who embraced a new paradigm would see things in an entirely different way, as if they were wearing glasses with inverting lenses. Many of Kuhn's readers thus concluded that Kuhn's theory of scientific revolutions denied rational comparisons between rival paradigms.

To avoid criticisms of relativism, Kuhn later modified his theory of scientific revolutions, beginning in the postscript to *Structure*. He abandoned the Gestalt analogy and developed a language metaphor: scientists who embraced rival paradigms would experience difficulties when they spoke to each other, as if they were members of different language communities. In the early 1980s, Kuhn (1983) took another step to narrow the scope affected by revolutions by introducing a notion of "local incommensurability." During a scientific revolution, most of the terms common to the rival paradigms remain the same, and only with a small subgroup of terms do problems of translatability arise. With this revision, Kuhn hoped that his theory no longer implied incomparability of rival paradigms, because the concepts that remained unchanged between rival paradigms could offer a common ground for theory appraisal.

In his late writings that reflect his mature point of view, Kuhn characterized scientific revolutions in terms of taxonomic changes, i.e., transformation in classification of physical objects. In the early 1990s Kuhn introduced a theory of kinds, which limits the scope of scientific revolutions or, more precisely, the scope of meaning change during scientific revolutions, to a restricted class of terms. Roughly speaking, they are taxonomic terms or kind terms. In English they are terms that can take the indefinite article, such as count nouns and mass nouns (Kuhn, 1991).

This theory of kinds has two important implications. First, it significantly reduces the scope of scientific revolutions. Conceptual change during scientific revolutions occurs merely to a very restricted class—kind terms. In the context of science and in such disciplines as astronomy, physics, chemistry, and biology, kind terms are mainly object concepts. In this way, scientific revolutions involve only meaning changes of object concepts, at least in the domain of natural science. Accordingly, the thesis of holism that always characterizes Kuhn's philosophy of science has a new meaning. Kuhn had given up the global holism developed in *Structure*, and he instead emphasized a localist feature of revolutions. Rather than discussing such a global entity as a paradigm or a disciplinary matrix, which covers everything from methodology, epistemology, to ontology, Kuhn focused on a very limited class of entities—object concepts.

Second, Kuhn's theory of kinds fundamentally redrew the picture of scientific revolutions. Kind terms frequently function as categories in classification of physical objects. A group of kind terms forms a taxonomy in which there is a single superordinate in the group and the rest of the kind terms have proper inclusive relations with the superordinate and proper contrastive relations among each other. So, a scientific revolution is in effect a taxonomic shift, which produces a new taxonomy with some kind terms referring to referents that overlap with those denoted by some kind terms from the old taxonomy. In other words, a scientific revolution is a taxonomic shift that involves a redistribution of referents among existing object concepts, and a typical example of a scientific revolution is a transformation of a taxonomic system in which the new classification generates categories mismatching those of the old classification (Kuhn, 1991).

2.2. Scientific Revolutions as Taxonomic Shifts

Similar to Kuhn, many philosophers and historians of science also develop an object-only perspective on scientific revolutions, interpreting many important historical episodes of scientific revolutions as a kind of taxonomic change. For example, the Copernican revolution has been regarded as a change in the classification of celestial bodies (Kuhn, 1987), the chemical revolution as a redrawing of the taxonomy of substances (Thagard, 1992), and the Darwinian revolution as a restructuring of the kind hierarchy of biological organisms (Hull, 1989). Let's take a close look at the object-only pictures of the Newtonian revolution and the Copernican revolution, both of which are typical examples that philosophers and historians of science frequently use to illustrate the characters of scientific revolutions.

According to the object-only perspective, the Newtonian revolution included several significant taxonomic shifts by virtue of differentiating (decomposing taxonomic terms previously believed to be indivisible wholes) and coalescing (introducing a new superordinate category to cover two or more subordinates previously taken to be distinct). Before the revolution, for example, Aristotle's physics defined 'weight' as a measure of the proportion of the four elements in an object that determined the direction of its natural motion. Newton made a substantial change to distinguish 'mass' from 'weight'. In Newtonian physics, 'mass' is a property of an object (its quantity of matter) and 'weight' is a relationship between objects controlled by the force of gravity. This differentiation generated mismatches between the two taxonomic systems—the Newtonian 'mass' refers to some of the referents of the Aristotelian 'weight'. An example of taxonomic coalescence is Newton's abandoning of the Aristotelian distinction between 'celestial body' and 'terrestrial body'. In the Aristotelian system, celestial and terrestrial bodies are distinguished according to their nature and forms of motion. Celestial bodies are naturally in motion and take the form of circular motion. Terrestrial bodies are naturally at rest in their natural places, and if they are in motion, they move either upward or downward. In Newtonian physics, both celestial and terrestrial bodies are objects governed by the same set of mechanical laws. This coalescence did not simply combine two taxonomic terms but generated mismatches between the two taxonomies. Newtonian 'object' is not a conjunction of Aristotelian 'celestial body' and 'terrestrial body', because the nature of motion or rest implied by the Aristotelian distinction no longer exists in the Newtonian concept.

According to the object-only perspective, the Copernican revolution consisted in a dramatic transformation in the classification of celestial objects. Before the revolution, Ptolemy treated the earth as a unique kind because it was believed to be the center of the universe, and he grouped the sun, the moon, and planets together under one category because they all rotate around the earth. The contributions of Copernicus, according to this interpretation, mainly consist in a redistribution of celestial objects that he made across the taxonomy. Copernicus had initiated a revolutionary taxonomic shift by branch jumping, i.e., by moving a taxonomic category from one branch of the taxonomy to another (Thagard, 1992). For example, the Copernican taxonomy moved 'sun' from the class of 'planet' to the class of 'star', moved 'earth' from a class of itself to the class of 'planet', and moved 'moon' from the class of 'planet' to a new class of 'satellite'. Because of these reclassifications, many mismatches occurred between the Ptolemaic and the Copernican taxonomies. The Copernican taxonomy of celestial objects was incommensurable with the Ptolemaic taxonomy, mainly because of the following two outstanding changes. First, the sun in the Copernican taxonomy was moved from the category that includes planets and the moon to become a unique kind, because it is the center of the solar system. Second, the earth and planets in the Copernican system were grouped together because they all rotate around the sun. In this way, the Copernican revolution is frequently characterized as a transformation in cosmology, from a geocentric system to a heliocentric system.

3. Knowledge of Temporal Processes

3.1. The Ontological Tree

Since our knowledge of sensible noun–predicate combinations has its ontological root, we can identify our ontological knowledge about the nature of entities in the world through analyzing the combinations of nouns and predicates that we find sensible. Taking this direction, Keil (1979) offered a detailed analysis of a variety of sensible noun–predicate combinations, and described their relationships in the form of a hierarchical structure, called a *predicability tree*.[4] Figure 1 illustrates a predicability tree. In the figure, predicates are represented as nonterminal nodes in a tree-like structure, shown in uppercase letters, and nouns are represented as terminal nodes, shown in lowercase letters. Predicate–predicate connections are represented by solid lines and predicate–noun connections by dotted lines. Every nonterminal node in the predicability tree represents an indefinitely large class of predicates that can be sensibly applied to the same type of nouns, but only two examples from each class are shown in the figure. For example, the node with 'is asleep' and 'is hungry' would also contain many other predicates that belong to the same type, such as 'is awake' and 'is frightened'. Similarly, every terminal node in the predicability tree represents an indefinitely large class of nouns that can sensibly be associated with the same types of predicates, only two of which are shown in the figure. This predicability tree contains 13 predicate-nodes and nine noun-nodes. There are inclusion relations between predicate nodes at different hierarchical levels in terms of the extent of applicable nouns. Specifically, a predicate is applicable to all those nouns to which every underneath predicate is applicable. For example, the predicate 'is sick' can be applied to all nouns to which the predicates 'is asleep' and 'is wilted' are applicable. Thus, the higher a predicate in the tree, the more nouns it

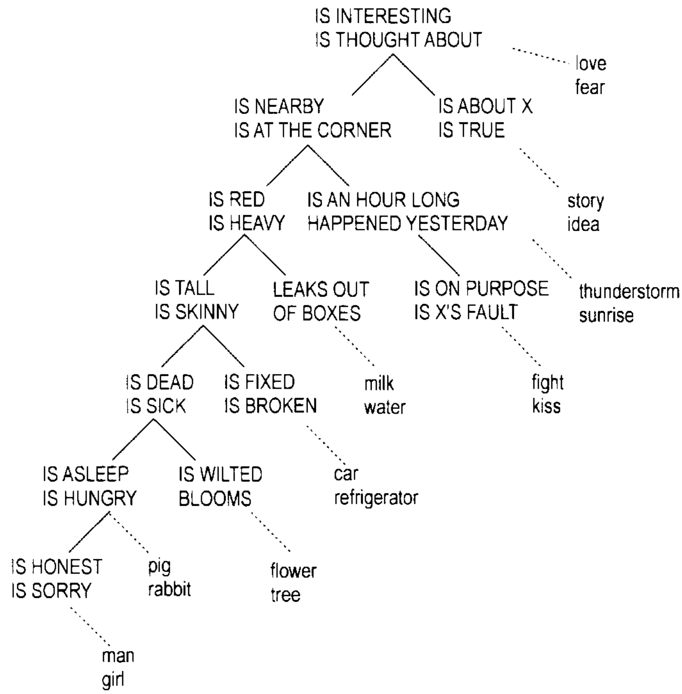

Figure 1. Keil's predicability tree. Reproduced from Keil (1979).

can be applied to, and the highest node in the tree contains such predicates as 'is interesting' that can be applied to all nouns.

Because of the inclusion relations between predicate nodes, each predicate node in the tree is associated with classes of nouns. For example, the node with the predicate 'is heavy' is associated with a set of several classes of nouns that forms a category denoting all physical objects. According to Keil (1979), "The result is that every node in the tree represents a class of terms which in turn denotes members of a certain ontological category. Thus, isomorphic to the predicability tree is an ontological tree with a different ontological category at each node" (p. 15). Figure 2 illustrates an ontological tree. In this figure, ontological categories are shown in uppercase letters, and examples of ontological categories are shown in lowercase letters. Also, inclusion relations between ontological categories are represented by solid lines and kind-of relations between a category and its examples by dotted lines. This is a hierarchical system. To begin with, it divides all things into two categories: THING WITH SPATIAL LOCATION and ABSTRACT OBJECT. Next, it divides THING WITH SPATIAL LOCATION into two subcategories, PHYSICAL OBJECT and EVENT (i.e., TEMPORAL PROCESS). At the next level, PHYSICAL OBJECT is divided into SOLID OBJECT and AGGREGATE, while EVENT is divided into INTENTIONAL EVENT and NON-INTENTIONAL EVENT. To SOLID OBJECT, divisions continue through several additional levels.

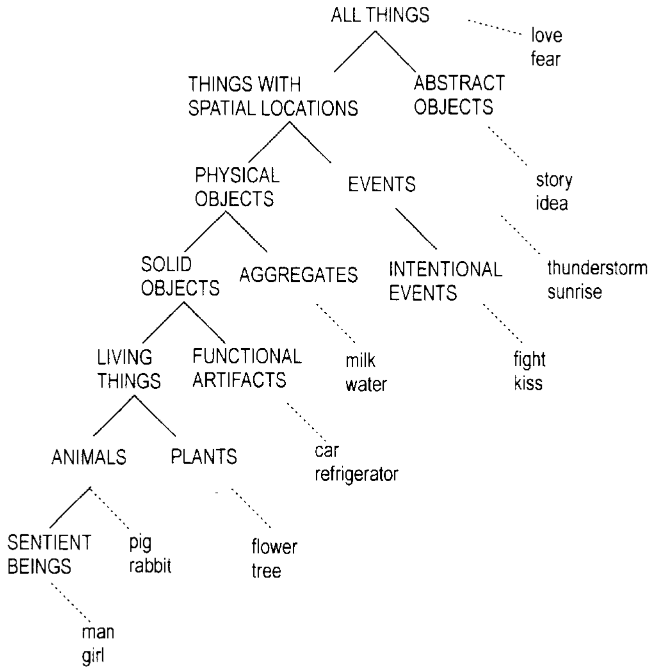

Figure 2. Keil's ontological tree. Reproduced from Keil (1979).

3.2. When do Children Distinguish Processes From Objects?

According to Keil, ontological knowledge in the form of the ontological tree is not innate. In the early stage of cognitive development, children have an incomplete ontological tree, which distinguishes only a few ontological kinds and treats the rest as the same. As children grow, their ontological knowledge evolves and their ontological tree begins to distinguish more and more ontological kinds. In general, it takes about ten years to complete this cognitive development.

In a series of experiments that involved more than 300 children, including kindergartners, second-graders, fourth-graders, and sixth-graders, Keil (1979) investigated the development of ontological knowledge. In these experiments, Keil focused on children's knowledge of anomalous sentences. He gave the children sentences containing noun–predicate combinations, and asked them to judge which noun–predicate combinations were silly or impossible. From each child's responses, he constructed a predicability tree that reflected the child's ontological knowledge. Figures 3–5 show three sample trees generated by a kindergartner, a second-grader, and a fourth-grader.

Figure 3 illustrates the predicability tree generated from data provided by a 5-year-old kindergartner (Keil, 1979, Figure 24). It contains only two ontological categories: one for living things and the other for everything else. This kindergartner's

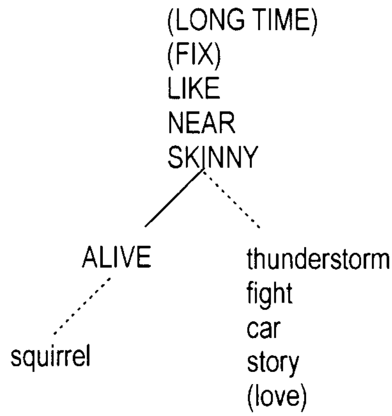

Figure 3. The predicability tree of a kindergartner. Reproduced from Keil (1979).

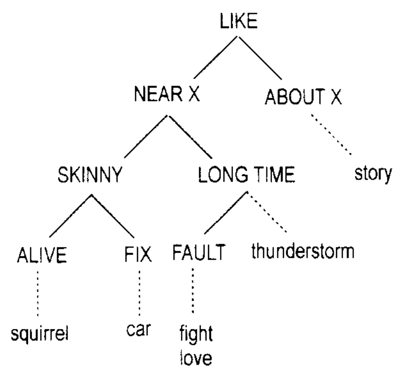

Figure 4. The predicability tree of a second-grader. Reproduced from Keil (1979).

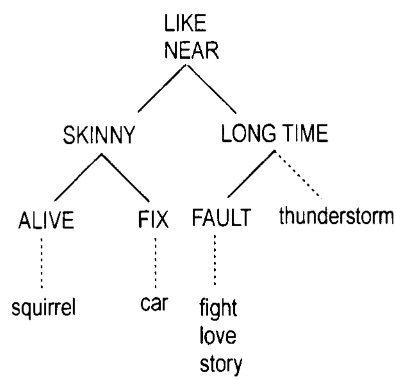

Figure 5. The predicability tree of a fourth-grader. Reproduced from Keil (1979).

category of LIVING THING is virtually the same as adults', including humans, animals, and plants as its examples. But the category of EVERYTHING ELSE is interesting. It contains not just physical objects such as cars, but also temporal processes such as fights and abstract entities such as stories. It is evident that this kindergartner did not differentiate abstract entities and temporal processes from physical objects. He sincerely believed that a fight could be fat and a story could be skinny, and he gave many "I don't know" answers to questions involving the predicate 'took long time'. The confusion between physical objects and temporal processes was common among others in the same age group. Although some of them might have some vague preliminary knowledge of temporal processes, they knew neither that temporal predicates could not apply to all things, nor that temporal terms could not denote things with physical dimensions.

Figure 4 represents the predicability tree generated from data provided by a 7-year-old second-grader (Keil, 1979, Figure 26). Several significant changes emerge in this tree. It distinguishes three ontological categories: one for living things, one for functional artifacts, and one for temporal processes. This second-grader began to differentiate temporal processes from physical objects. When he was asked if a car could be an hour long, he responded, "Silly, hour doesn't measure a car." However, this second-grader continued to treat temporal processes and abstract objects as the same kind by applying temporal predicates such as 'long time' to 'story' and 'love'. During the same time, this second-grader and several others in this age group applied 'was x's fault' only to 'story' and 'love', but not to 'thunderstorm'. This suggests that they distinguished natural and intentional events, and regarded certain abstract objects as intentional events.

Figure 5 represents the predicability tree generated from data provided by a 10-year-old fourth-grader (Keil, 1979, Figure 27). A significant change in this tree is that it distinguishes abstract objects from temporal processes. This fourth-grader had a clear notion of the predicate 'is about x', which he combined only with the noun 'story'. This predicability tree is quite similar to the one generated by adults (Figure 1), with only a few differences. For example, it does not further distinguish those examples of 'living thing', and it treats 'love' as an intentional event rather than as an example of 'all things' in the adult tree.

By comparing these predicability trees, Keil showed the origins and development of adults's ontological knowledge. It develops gradually from the fragments of the ontological knowledge that we have acquired during childhood, and increased differentiation is the principal pattern of this development. With increased age, we are able to understand more ontological categories. According to Keil, differentiation of ontological knowledge always proceeds in an ordered fashion. Differentiation between living things and other physical objects is first recognized in this process, followed by the one between functional artifacts and other physical objects, then the one between temporal processes and physical objects, and finally the one between temporal processes and abstract objects. Furthermore, differentiation of ontological knowledge also proceeds in an asymmetrical fashion, in the sense that new ontological categories appear to develop out of old ones rather than out of syncretic complexes. This suggests the following sequence of category development:

1. Physical objects.
2. Living objects out of nonliving physical objects.
3. Functional artifacts out of other nonliving physical objects.
4. Temporal processes out of physical objects.
5. Intentional events out of natural events.
6. Abstract objects out of temporal processes.

3.3. How do Children Distinguish Processes From Objects?

From developmental studies, we learn that children begin to understand the distinction between physical objects and temporal processes around the age of 7. How does this ontological differentiation take place? Does it occur suddenly or gradually? Specifically, when a child begins to understand the differences between physical objects and temporal processes, does she suddenly sort out all the relevant nouns and predicates according to the ontological distinction, or gradually separate the two groups in a more incremental fashion? Keil (1983) conducted a series of experiments to answer these questions.

The subjects of these experiments were 24 children, eight each from kindergarten, second-grade, and fourth-grade. The children were given noun–predicate combinations generated from a list of predicates (four object predicates and four temporal predicates) and a list of nouns (three object nouns and three temporal nouns), and asked to judge which noun–predicate combinations are acceptable. The focus was to investigate senseless combinations. If the ontological differentiation occurs gradually, some children should be in intermediate stages where they mistakenly use some of the predicates but not all. But if the differentiation occurs suddenly, no such intermediate stages should exist. Misapplications of predicates, i.e., using an object predicate to describe a temporal noun or the other way around, should happen in an all-or-none fashion.

The results of the experiments support the sudden differentiation account. Among the 21 subjects who had misapplied object predicates to temporal nouns, 19 did so to all four object predicates. Only two were able to limit the misapplications to some of the predicates but not all. A similar pattern also exists in the misapplications of temporal predicates to object terms. Among the 21 instances of misapplications of temporal predicates, 15 did so to all four temporal predicates (Keil, 1983, Tables 1–2). Thus, it seems that object and temporal predicates are either all collapsed together or separated into two coherent groups as soon as the ontological distinction is made. In the experiments, the subjects did not learn the distinction by inductive generalization. They did not initially discover that the predicate 'is red' could not apply to 'recess' and then gradually extend that insight to other object predicates. Instead, all the predicates belonging to the same ontological type appear to be tightly linked together, and the awareness of the misapplication of any one predicate to a given noun immediately entails that all other predicates from the same group also cannot be applied to the same noun.

Sudden differentiation, however, is not a general pattern for all ontological distinctions. Keil had also investigated how the distinction between animals and plants takes place, but he found a very different pattern. For example, among the 61 subjects who had misapplied animal predicates to a plant noun, only four did so to all animal predicates (Keil, 1983, Table 8). The rest were able to limit the misapplications to some of the predicates but not all. In fact, the majority, 40 subjects, only misapplied one animal predicate and used the other three correctly. Apparently, the subjects learned the meanings of each predicate individually, independent of others from the same group.

According to Keil, it is not surprising to find two patterns of ontological differentiation. First, the differences between animals and plants are dissimilarities between types of physical objects, a general category that children understand in the first stage of cognitive development. Thus, acquiring the distinction between animals and plants represents a subtle awareness of certain details and can be achieved incrementally. On the contrary, acquiring the distinction between physical objects and temporal processes represents a totally new awareness to most children, and can only be achieved in a revolutionary fashion. Furthermore, unlike animals and plants that can be neatly and easily demarcated in terms of numerous perceptual properties, physical objects and temporal processes cannot be distinguished in terms of any perceptual properties. The distinction between physical objects and temporal processes rests on a conceptual awareness that there are some things that have no object properties whatsoever.

Sudden differentiation between physical objects and temporal processes implies that the distinction between these two ontological categories is fundamental, because it seems to involve deeper, nonlinguistic changes that influence a whole category of words. In Keil's (1983) words, the conceptual distinction between object and temporal concepts "is discovered at some deeper level that encompasses all the relevant properties that can be stated in a natural language" (p. 370).

Sudden differentiation between physical objects and temporal processes further indicates that we do not develop the ability to recognize temporal processes gradually by separating the two ontological kinds in an incremental fashion. When children begin to understand the differences between the two ontological kinds, they gain this ability instantly, in the manner of a sudden enlightenment. This phenomenon suggests that the development from an object-only perspective to one that distinguishes between objects and processes is fundamental and revolutionary. This is a transformation from the perspective tainted by the object bias to one that properly treats objects and processes as distinct ontological kinds.

4. Knowledge of Physical Objects

4.1. A Core System of Object Knowledge

Unlike knowledge of temporal processes, children develop a core system of object knowledge at the very beginning of their lives. Recently, studies from developmental psychology report that awareness of object permanence emerges among infants as young as 4 months of age. These experiments employ a specially designed technique—the method of preferential looking time—to investigate what nonverbal infants know about the world. In general, this technique begins with a series of habituation trials to remove the effects of novelty on the infants to displayed events. Subsequently, the infants are presented with test events that are either consistent or inconsistent with their expectations according to their understanding of the physical world. Events consistent with expectations are possible and thus do not draw special attention. Events inconsistent with expectations, however, are impossible and should draw the attention of the infants. Consequently, the infants should spend more time looking at impossible than at possible events. By recording looking times to both possible and impossible events, developmental psychologists can uncover nonverbal infants' expectations of the physical world.

Using the looking-time method, Baillargeon and her colleagues designed a series of experiments to investigate when awareness of object permanence emerges. In one of these experiments (Baillargeon, Spelke, & Wasserman, 1985), they habituated babies in front of a rotating wooden screen, revolving 180 degrees toward and away from the infants. After habituation, they put a solid box behind the screen while the screen lay flat, so that the infants could clearly see that the box was in the path of the rotating screen. Then the screen was raised, hiding the box from the view of the infants. In this experiment, the infants were shown a possible and an impossible test event. In the possible event, the screen moved away from the infants until it reached the occluded box, stopped, and then returned to its initial position. In the impossible event, the screen moved away until it reached the box, and then continued to move as if the box were no longer behind it (see Figure 6). The 4- to 5-month-old infants in this study remained habituated when viewing the possible event, but showed surprise when viewing the impossible event: their looking times for the impossible event were almost double those for the possible event.

These results show that the 4-month-old infants knew that the box continued to exist in the same location after it was occluded by the screen. This is an indication that infants at this age begin to develop early awareness of object permanence. Furthermore, Baillargeon's work also shows that the infants in the experiment understood that the screen could not move through the space occupied by the box. This suggests that infants as early as 4 months of age also know that two solid objects cannot be in the same place at the same time.[5]

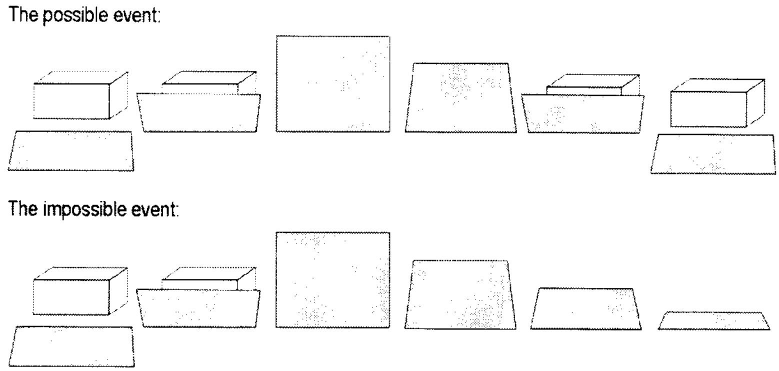

Figure 6. Schematic representation of Baillargeon's experiment. Reproduced from Baillargeon et al. (1985).

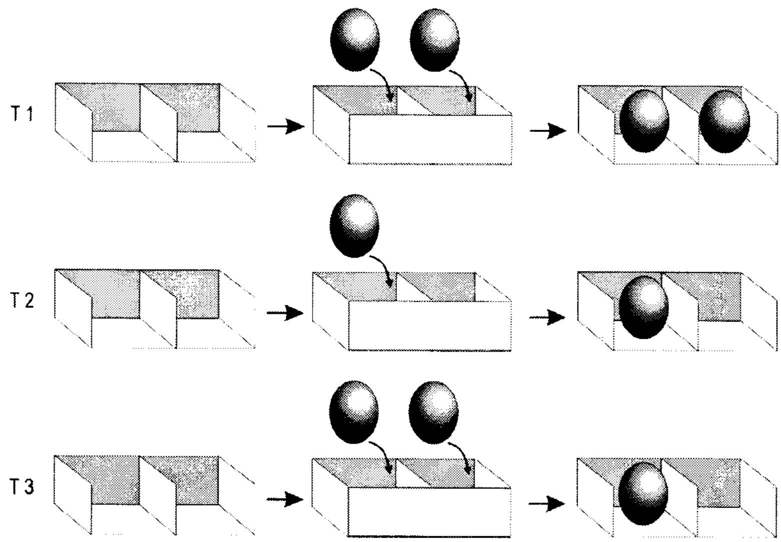

Figure 7. Schematic representation of Hauser & Carey's experiment. Reproduced from Carey (2001).

Researchers also use the looking-time method to investigate awareness of object permanence in nonhuman subjects. For example, Hauser and Carey conducted a series of experiments that used wild rhesus monkeys as the subjects. In one of these experiments (Carey, 2001), they employed three different trials (see Figure 7). In Trial 1, the monkeys were first shown the empty box. Then the screen was inserted in front of the box and two eggplants were placed in the box, one after another. Finally, the screen was removed, revealing the expected outcome of two eggplants in the box. Trial 2 was similar to Trial 1, except that only one eggplant was placed in the box and one eggplant was revealed when the screen was removed. Both Trials 1 and 2 were possible events. Trial 3, however, was an impossible event, in which two eggplants were placed in the box but only one eggplant was revealed when the screen was removed. Hauser and Carey found that, like human babies, the monkeys showed surprise when viewing the impossible event. The monkeys consistently looked longer at the impossible outcomes of Trial 3 than at the possible outcomes of either Trial 1 or Trial 2.

Hauser and Carey's experiment shows that rhesus monkeys are able to establish representations of objects, and to maintain these representations through time when the objects are out of view. This is an indication that rhesus monkeys have basic awareness of object permanence. Further, similar experiments performed by other researchers show that a wide range of primate species, from chimpanzees to evolutionarily distant cebus monkeys, can solve simple object permanence tasks as well as 15- to 18-month-old human infants (Natale & Antinucci, 1989). These experiments on nonhuman subjects, together with those on nonverbal infants, suggest that awareness of object permanence and solidity may be an innate endowment, or a part of humans' primate heritage.

According to Carey and Spelke (1994), children's innate cognitive endowment consists of a set of core systems of knowledge. These core systems are domain-specific, each of which applies only to a distinct set of entities and phenomena. There are at least four core systems including knowledge of objects, agents, number, and space. Each core system of knowledge contains a distinct body of principles that allow infants to identify entities in the domain and make inferences about these entities. For example, the core system of object knowledge includes several principles on object motion, such as solidity (objects move on unobstructed paths, such that two objects never occupy the same place at the same time), coherence (objects maintain their boundaries as they move), continuity (objects move only on connected paths), and contact (objects move together only if they are in contact). Because of this core system of object knowledge, infants are able to solve a host of problems related to physical objects, including some relatively complicated problems such as the one about hidden objects in Baillargeon et al.'s (1985) experiment described above.

Carey and Spelke (1996) also suggest that the core system of object knowledge is primarily innate, arising from a phylogenetically old system built upon the output of innate perceptual analyzers. When infants grow and learn new facts about physical objects, a part of this core system of object knowledge remains intact and evolves to become adults' commonsense understandings. Adults who are engaged in commonsense reasoning never completely give up this core system of object knowledge, because it effectively accounts for many phenomena in daily life. Even in the domain of physics, the principles of coherence, continuity and contact continue to be central for students as they develop an intuitive understanding of notions of object persistence and object motion (Hirsch, 1982; Spelke, 1991).

Further evidence for the existence of the core system of object knowledge among adults comes from studies of science education. Typically, introductory physics courses start with discussions of point particles. Students, both at the high school and at the college levels, usually do not experience too much trouble in comprehending particle motions, because particle kinematics and particle dynamics are consistent with the core system of object knowledge. However, numerous problems appear when discussions move from particles to extended bodies, such as the motion of wheels. At this junction, students experience profound difficulties if they continue to rely on the core system of object knowledge to understand the new phenomena, because the physics of extended body motions requires abstract mathematical analyses and can no longer be reconciled with the commonsense understanding based on perception.

Not only naïve students but also experts tend to apply the core system of object knowledge to complicated physical phenomena. Even high school physics teachers and university physics professors exhibit confusions similar to those found in naïve students if they are forced to answer questions quickly or if they are not allowed to make explicit calculations. In an experiment, Proffitt and Gilden (1990) tested whether their subjects, 50 professors of physics, could correctly understand the motions of two wheels with identical mass and radius but different mass distribution (a solid wheel and a rimed wheel). They asked the subjects to predict, when these wheels were placed at the top of an inclined plane, whether they would arrive at the bottom at the same time. Without making mathematical analyses, 80% of the subjects incorrectly predicted that the wheels would roll down the inclined plane at the same rate, a performance similar to those of naïve undergraduates. Apparently, when these experts of physics were prohibited from solving the problem analytically, they went back to rely on the core system of object knowledge. They failed to predict the result correctly, not because they appealed to erroneous theories, but because they appealed to the core system of object knowledge that is intrinsically limited in dealing with complex dynamic systems. Since the core system of object knowledge is based on perceptual information, the subjects in the experiment continued to be perplexed even after observing how the wheels were actually rolling down the inclined plane. This experiment indicates that the core system of object knowledge is well entrenched, and adults, including experts, prefer to rely on this core system of knowledge whenever it is possible.

4.2. The Preference for Objects in Science Education

Adults also prefer to apply the core system of object knowledge to phenomena that belong to different ontological categories, and consequently develop an object bias. Accordingly, we can find evidence for the object bias in the field of science education. Researchers in science education have found that many difficulties experienced by both students and teachers in physics classrooms originate from widespread misconceptions of certain physics concepts. Some students attach themselves to false conceptions of some important notions in physics, and consequently they are unwilling to accept the conventional views of these notions offered by their instructors. These misconceptions in physics education are robust in the sense that they are difficult to overcome by instruction (Chi, Slotta, & de Leeuw, 1994). Research shows that these misconceptions are consistent over time and situation—typically the same students display the same misconception over different times and different contexts. These misconceptions are also persistent across different ages and school levels—elementary school, high school, and even college students all maintain the same sort of misunderstanding. To account for the robustness, consistency, and persistency of misconceptions in science education, Chi (1992) offered an incompatibility hypothesis: Students of science experience robust, consistent, and persistent difficulties because they mistakenly assign certain scientific notions to an incompatible ontological category. For example, novice students tend to view concepts of HEAT, LIGHT, ELECTRICITY, and FORCE either as material substances or properties of material substances. But in the eyes of experts, all of these concepts refer to temporal processes. The confusion between physical objects and temporal processes is one of the roots of the widespread misconceptions among students of science.

Chi and her collaborators designed an experiment to test this hypothesis (Slotta, Chi, & Joram, 1995). They compared the performance of two kinds of subjects: ninth-grade students (novices) and graduate students of physics (experts). Subjects were first presented a set of physics-concept problems concerned with one of the following three concepts: LIGHT, HEAT, or ELECTRIC CURRENT. For example, one of the physics-concept problems required the subjects to predict which of two cups of coffee, one in a Styrofoam cup and the other in a ceramic mug, would be hotter 20 minutes after they were poured. The subjects were asked to select a correct answer from a list of four choices, and then to explain their choice in terms of the underlying causes and structures. After this set of physics-concept problems, the subjects were then presented a set of material-substance problems, which were isomorphic to the first set of problems if processes in physics-concept problems were misconceived as material substances. For example, the corresponding material-substance problem isomorphic to the problem of comparing two cups of coffee asked the subjects to predict which of two balloons, one made of an ordinary paper bag and the other made of durable elastic rubber, would be more buoyant after several hours. The incompatibility hypothesis predicted that the novices would respond to physics-concept problems as if they were simply alternative versions of the respective material-substance problems.

The novices' responses to the multiple-choice questions demonstrated their confusion between physical objects and temporal processes. Although both the novices and the experts achieved nearly perfect performance on the material-substance problems, they differed greatly in their responses to physics-concept problems. While the experts had perfect performance (100%), the novices solved less than a half of the problems correctly (45%). More importantly, when the novices chose an incorrect answer to a physics-concept problem, they chose the one corresponding to the material-substance problem more often (64%) than the alternatives. To the problem regarding two cups of coffee, for example, many novices picked the wrong choice ("The coffee in the ceramic mug is hotter") because they might have viewed it as isomorphic to the corresponding material-substance problem in which the right answer was that "The balloon made of rubber is more buoyant."

The novices' explanations to their multiple-choice selections further displayed the extent to which their understanding of the physics-concept problems relied on the isomorphic material-substance concepts. Contrary to the experts, the novices tended to use the same type of predicates in their accounts for both physics-concept and material-substance problems. They mainly relied on a set of predicates that reflect the ontological characteristics of physical objects, such as 'block' (objects have volume and occupy space) and 'contain' (objects are containable). The preference for these object predicates suggests that the novices might have a naive ontological commitment to physical objects, which explains why some misconceptions in science education are robust, consistent, and persistent.

4.3. The Preference for Objects in the History of Science

Some of novices' misconceptions of scientific concepts, particularly their naive ontological commitment to physical objects, are recapitulated across historical periods. Many centuries ago, mature scientists had the same misconceptions as those held by contemporary naive students.

A good example of historical recapitulation comes from the domain of thermal physics. Studies of science education show that, before formal instruction, students usually conceptualize thermal phenomena in ways fundamentally different from scientists. The core of their conceptions of thermal phenomena is that heat is a mysterious entity with the essential property of hotness. When they are asked to envision a piece of steel on a hotplate, for example, they typically describe the phenomenon as that the hotplate, as an active source, emits heat spontaneously, and then heat spreads through the steel piece because it is pushed by the incoming heat from the hotplate (Wiser & Amin, 2001). Later, when they learn kinetic molecular theory, they usually accept a part of it, but resist the idea that what the hotplate provides to the steel bar in the above example is molecular kinetic energy. They frequently come up with various conversion schemes, either that the energy provided by the hotplate must convert into hotness or that the molecular movements in the steel bar must be initiated by the heat from the source.

After conducting a protocol analysis of the works of a group of 17th-century scientists who called themselves "the Experimenters," Wiser and Carey (1983) report that these historical figures had misconceptions of thermal phenomena very similar to those of contemporary novices. Similar to today's students of physics, the Experimenters viewed heat as something emitted by hot source, with an essential property of hotness. All hot bodies were spontaneous emitters, projecting particles of heat, or atoms of fire. Because heat was a material substance, it could causally change the state of other objects. When an object was placed next to a hot source, particles of heat from a hot source could push, thrust, or impact on the substance of the object and thereby cause the spread or transmission of heat. Thus, the Experimenters in the 17th century and contemporary naive students of physics have misunderstood heat in the same way—both have viewed heat as physical objects.

Similar historical parallels also exist in the theories of motion. McCloskey (1983) has identified similarities between the contemporary naive theory of motion popular among students of physics and the medieval theory of impetus discussed by Philoponus in the 6th century and developed by Buridan in the 14th century. Both of these theories propose that continuing motion must be sustained by impetus or force. To explain why constant contact is needed to maintain a motion, both theories assume that impetus or force is a material-like substance that can be processed, transferred and dissipated, so that an agent is needed to supply the impetus. Again, the medieval theory of impetus and the contemporary naive theory of motion misunderstand force in the same way—both view it as a material substance.[6]

5. A Redrawing of the Copernican Revolution

Recent findings from the history of science show that the object-only perspective on the Copernican revolution is in conflict with various historical facts. As pointed out by many historians, including Peter Barker, Bernard Goldstein, and Robert Westman, there was a consensus among 16th century astronomers, including Copernicus himself, that the goal of astronomy was to describe planetary positions seen by an observer on the earth against the sphere of the heavens as the background. From antiquity to the 16th century, astronomers devoted most of their attention to recording and calculating planetary positions or, more precisely, the planets' longitudinal positions at different times. With this goal in mind, most 16th-century astronomers found the conceptual structure behind Copernicus's calculation techniques to be the same as the one behind Ptolemaic astronomy. Copernicus accepted Ptolemy's calculation techniques and he did not introduce any new concepts. He was even more consistent than Ptolemy in following the Aristotelian tradition of using uniform circular motions only to describe celestial objects. Although he moved the center of celestial motions from the earth to the sun, this did not make any substantial difference in astronomical calculations. Within the conceptual system of 16th-century astronomy, using the mean sun as the center was similar to a calculation technique used already by Ptolemy, which assigned a point different from the center of the earth as a new center for the eccentric circle. In fact one could generate a Copernican system from a Ptolemaic one by swapping the sun and the earth–moon combination (Barker & Goldstein, 1998). This is why most 16th-century astronomers did not regard Copernicus as undermining Ptolemy's astronomy, but as amending and improving it by avoiding such a deviant conceptual structure as the *equant*. The Wittenberg interpretation of Copernicus, which appeared in a "letter to the reader" directly after the title page of *De Revolutionibus*, reflected this view. It simply treated Copernicus' system as a new calculation technique and totally disregarded its cosmology and the implied taxonomy. This was the most influential interpretation of *De Revolutionibus*, from the death of Copernicus in 1543 until the appearance of the major works by Kepler and Galileo in 1609 and 1610 (Barker, 2002; Westman, 1975).

As indicated by these historical facts, Copernicus was not really a revolutionary figure in the so-called Copernican revolution, and the revolutionary change in astronomy during the 16th and 17th centuries should not be characterized as a transformation from a geocentric system to a heliocentric system. Many historians have recently pointed out that the real revolutionary figure in this revolutionary change was Kepler, and the key achievement of the so-called Copernican revolution consists in transforming theoretical astronomy from one that was understood in terms of ORB to one that was understood in terms of ORBIT (Barker, 1990; Barker & Goldstein, 1998; Goldstein & Hon, 2005). From antiquity to the 16th century, astronomy was built on a specific ontology that attached planets to spherical shells called *orbs*. The evidence against orbs was not available during the time of Copernicus, and he continued to view planets as being carried by their orbs. Evidence against orbs appeared first in 1577, from the observations of a comet. Maestlin and Brahe recorded the comet's positions over a period of months, and they found that the track of the comet cut through several orbs assumed by Ptolemy's system. But neither Maestlin nor Brahe was able to give up the concept of ORB completely. It was Kepler, as the intellectual heir of both astronomers, who was able to see the possibility of replacing spherical orbs with orbits.

The concept of ORBIT first appeared in *Astronomia Nova* of 1609, where Kepler presented a picture of the orbit of Mars by drawing the track of Mars as a continuous curve in two dimensions. Abandoning the concept of ORB had a very important, revolutionary implication. As soon as the material orbs were abandoned, the question of what moves the planets became acute. Like most of his contemporaries, Kepler still accepted the notion of inertia, believing that objects move only while a force acts on them, and that the motion is in proportion to the intensity of the force. Also like many of his contemporaries, Kepler was deeply influenced by Neo-Platonism that assigned to the sun a special, or even mystical, power. Thus, Kepler assumed that the force responsible for moving the planets was located in the physical sun. This was a revolutionary change. For the first time in the history of astronomy, the sun was assigned not just a geometric role, as a center of celestial motion, but also a physical role, as the cause of celestial motion. Also for the first time in the history of astronomy, astronomical phenomena were not just described, but also explained by physical causes that were characterized by physical laws.

The conceptual change from ORB to ORBIT was not one between two object concepts. The Ptolemaic notion of ORB is an object concept, which can be characterized by its spatial features such as its geometrical center, its radius, and its rotating speed designated by its angular velocity (Barker, 2002). An orb consists of matter of some kind (aether), and it has solidity and shape. An orb endures over time so that it is temporally permanent. Finally, an orb occupies space and its occupancy is exclusive. Two orbs cannot occupy the same place at the same time—this was exactly the issue that got Brahe's system into trouble.

The concept of ORBIT, however, has fundamentally different ontological features. At first glance, it seems that an orbit, like an orb, can also be characterized by its center, radius (or distance as Kepler preferred), and speed. But in Kepler's conceptual framework, an orbit does not consist of matter of one kind or another, and an orbit does not occupy space exclusively (so that two orbits, such as the one of the earth and the one of the moon, can occupy the same place at the same time). More importantly, an orbit is not temporally permanent. Neither its distance nor its speed can have a stable value—their values always vary during the course of each complete orbit. The key to characterize an orbit is to describe a process of planetary motion, in which the value of distance varies from smallest to largest, while the value of speed changes from fastest to slowest correspondingly. Thus, ORBIT is not an object but a process concept.

Armed with the distinction between object concepts and process concepts, we can redraw the picture of the Copernican revolution. This is a dramatic reappraisal of the historical episode. Rather than seeing it as a taxonomic change from a geocentric to a heliocentric cosmology, we now see the Copernican revolution as a transformation from an astronomy that was based on an ontology of an ORB to one that analyzed the cosmos in terms of an ORBIT or, more precisely, as a transformation from a conceptual system that was built around the object concept ORB to one that was built around the process concept ORBIT. In short, the Copernican revolution was a conceptual change across different ontological categories.

6. Conclusion

The distinction between physical objects and temporal processes can enrich our understanding of many important historical episodes of conceptual change. Not all scientific revolutions, or more generally, not all evolutions of scientific knowledge, occurred as transformations between object concepts. Scientific revolutions have a variety of formats that involve different kinds of ontological entities.

Scientific revolutions can take the form of transformations from object to process concepts, exemplified by the Copernican revolution. We can also find examples of this kind of conceptual change in the optical revolution, the disruptive replacement of the particle theory by the wave theory of light at the beginning of the 19th century. Historians of optics have noticed that polarization, the phenomenon that rays of light exhibit different properties in different directions, was the most difficult subject in the optical revolution. Many contemporaries, including John Herschel, failed to understand the wave account of polarization. Although he was the most important founding figure of the wave tradition in Britain, Herschel's understanding of the wave theory was inconsistent. He did not have trouble in comprehending most doctrines of the wave theory, including the theory of reflection and refraction, the principle of interference, and the account of diffraction, but evidently he was confused when he dealt with polarization. To understand Herschel's confusion, the key is to see that the particle and the wave accounts for polarization were built upon two ontologically distinct concepts—the object concept of SIDE from the particle framework and the process concept of PHASE DIFFERENCE from the wave framework. Failing to complete the transition from an object to a process concept was one of the cognitive sources for Herschel's confusion. Thus, the optical revolution also involved a transformation from an object to a process concept (Chen, 2003).

Scientific revolutions can take a reverse format, as transformations from a process concept to an object concept. An example of this kind of scientific revolution can be found in the transition from the Maxwellian to the Lorentzian concept of CHARGE. According to Maxwell, electronic charge is the phenomenon corresponding to a process of stress change in the medium, but according to Lorentz, electronic charge is the property of an electron, a physical object (Nersessian, 1984). Thus, the transition from Maxwellian to Lorentzian electromagnetic theory required a concept change from a process concept to an object concept. This was also a conceptual change across different ontological categories, and there is no reason to believe that it would be in any way easier than those that occur in the opposite direction from object concepts to process concepts.

Scientific revolutions can also take the form of transformations between process concepts. An example of this kind of scientific revolution can also be found in the history of optics. This is the conceptual change from LONGITUDINAL WAVE to TRANSVERSE WAVE, a transformation critical to the development of the wave theory of light in the early 19th century. Both LONGITUDINAL WAVE and TRANSVERSE WAVE are process concepts. To complete the transition from LONGITUDINAL WAVE to TRANSVERSE WAVE, one must understand waves not as a dynamic process but as a kinematic process, and distinguish various kinds of wave processes not by spatial but by temporal characters. Only after we see this conceptual change as a transformation between process concepts can we understand why Young, a prominent wave theorist, failed to complete the transformation from LONGITUDINAL WAVE to TRANSVERSE WAVE (Chen, 2005).

Scientific revolutions can also take the form of transformation between different kinds of process concepts, denoting aimless processes and goal-driven events. A scientific revolution can take the form of changes from an event to a process concept, or the other way around. A typical example of conceptual change from an event to a process concept is the Darwin revolution. Undoubtedly, the Darwin revolution generated a new taxonomy of biological beings, but it cannot be reduced to a taxonomic change. The most significant contribution of Darwin, difficult to be understood by his contemporaries, is his effort in abolishing the teleological view of evolution. Before Darwin, all evolutionary theorists, such as Lamarck, Chambers, and Spencer, viewed evolution as a goal-driven event. The forms of human and contemporary living beings were seen as goals that provide the direction to the evolutionary process. On the contrary, Darwin recognized no goals in the evolutionary process. Evolution is driven by an aimless mechanism—natural selection—and thus it is a process that moves steadily from primitive beginnings but toward no completions. This is a very profound thought of Darwin. Even today, many of our contemporaries still fail to fully comprehend how evolution is possible without a goal (the popularity of intelligent design is a good example). Thus, viewing the Darwin revolution merely as a taxonomic change between object concepts would misinterpret the nature of this profound historical episode.

In conclusion, we need to adopt a new perspective on scientific revolutions. It is necessary to start a fundamental transformation from the object-only perspective to a temporal perspective or, more precisely, to an ontological perspective that properly treats objects and processes as distinct kinds. To achieve this transformation, we need to shake off the object bias that has influenced philosophy of science for decades, and to reexamine many of the assumptions, methods, and practices that we have taken for granted. In many ways, this transformation in the study of scientific revolutions itself is a revolutionary change.

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Notes

[1] In this paper, I define *temporal processes* as successions of changes that take place over time, including causal processes, events, activities, and mechanisms.

[2] Not every object has all of these properties. Amorphous objects such as clouds, water, and smoke have only a degree of solidity and they do not have stable shape. Nevertheless, they still consist of matter of one kind or another, and they are fundamentally different from shadows, rainbows, and patches of light, which do not consist of matter but are sensations generated by matter.

[3] For more on the ontological distinction between physical objects and temporal processes, see Hacker (1982) and Rescher (1996).

[4] Keil's analysis was built on Sommers' earlier work on "linguistic predicability" (Sommers, 1959, 1965).

[5] Experiments from developmental psychology also indicate that infants around the age of 4 to 5 months can distinguish one object from another by applying the continuity criterion for object individuation (Spelke, Vishton, & von Hofsten, 1995), and have developed awareness of certain spatial relations between objects (Mandler, 1992).

[6] Contemporary naive students' preference for physical objects is mainly developmental, caused by the persistent influence of the core system of object knowledge. Medieval scientists' preference for physical objects, however, was both developmental and philosophical. The preference for objects could originate from Aristotelian physics and metaphysics.

References

Baillargeon, R., Spelke, E., & Wasserman, S. (1985). Object permanence in 5-month-old infants. *Cognition*, *20*, 191–208.

Barker, P. (1990). Copernicus, the orbs and the equant. *Synthese*, *83*, 317–323.

Barker, P. (2002). Construction Copernicus. *Perspectives on Science*, *10*, 208–227.

Barker, P., & Goldstein, B. (1998). Realism and instrumentalism in sixteenth century astronomy: A reappraisal. *Perspectives on Science*, *6*, 232–258.

Carey, S. (2001). The representation of number in natural language syntax and in language of thought: A case study of the evolution and development of representational resources. In J. Branquinho (Ed.), *The foundations of cognitive science* (pp. 23–53). Oxford, England: Clarendon Press.

Carey, S., & Spelke, E. (1994). Domain-specific knowledge and conceptual change. In L. Hirschfeld & S. Gelman (Eds.), *Mapping the mind: Domain specificity in cognition and culture* (pp. 169–200). Cambridge, England: Cambridge University Press.

Carey, S., & Spelke, E. (1996). Science and core knowledge. *Philosophy of Science, 63*, 515–533.

Chen, X. (2003). Why did Herschel fail to understand polarization? The differences between object and event concepts. *Studies in the History and Philosophy of Science, 34*, 491–513.

Chen, X. (2005). Transforming temporal knowledge: Conceptual change between event concepts. *Perspectives on Science, 13*, 49–73.

Chi, M. (1992). Conceptual change within and across ontological categories: Examples from learning and discovery in science. In R. Giere (Ed.), *Cognitive models of science* (pp. 129–186). Minneapolis: University of Minnesota Press.

Chi, M., Slotta, J., & de Leeuw, N. (1994). From things to processes: A theory of conceptual change for learning science concepts. *Learning and Instruction, 4*, 27–43.

Goldstein, B., & Hon, G. (2005). Kepler's move from orbs to orbits: Documenting a revolutionary scientific concept. *Perspectives on Science, 13*, 74–111.

Hacker, P. (1982). Events and objects in space and time. *Mind, 91*, 1–19.

Hirsch, E. (1982). *The concept of identity.* New York: Oxford University Press.

Hull, D. (1989). *Science as a progress.* Chicago: University of Chicago Press.

Keil, F. (1979). *Semantic and conceptual development: An ontological perspective.* Cambridge, MA: Harvard University Press.

Keil, F. (1983). On the emergence of semantic and conceptual distinctions. *Journal of Experimental Psychology: General, 112*, 357–385.

Kuhn, T. (1970). *The structure of scientific revolutions.* Chicago: University of Chicago Press.

Kuhn, T. (1983). Commensurability, comparability, and communicability. In P. Asquith & T. Nickles (Eds.), *PSA 1982* (Vol. 2, pp. 669–688). East Lansing, MI: Philosophy of Science Association.

Kuhn, T. (1991). The road since structure. In A. Fine, M. Forbes, & L. Wessels (Eds.), *PSA 1990* (Vol. 2, pp. 3–13). East Lansing, MI: Philosophy of Science Association.

Mandler, J. (1992). How to build a baby: II. Conceptual primitives. *Psychological Review, 99*, 587–604.

McCloskey, D. (1983). Naive theories of motion. In D. Gentner & A. Stevens (Eds.), *Mental models* (pp. 299–324). Hillsdale, NJ: Erlbaum.

Natale, F., & Antinucci, F. (1989). Stage 6 object-concept representation. In F. Antinucci (Ed.), *Cognitive structure and development in nonhuman primates* (pp. 97–112). Hillsdale, NJ: Lawrence Erlbaum.

Nersessian, N. (1984). *Faraday to Einstein: Constructing meaning in scientific theories.* Dordrecht: Reidel.

Proffitt, D., & Gilden, D. (1989). Understanding natural dynamics. *Journal of Experimental Psychology: Human Perception and Performance, 15*, 384–393.

Rescher, N. (1996). *Process metaphysics: An introduction to process philosophy.* Albany, NY: State University of New York Press.

Slotta, J., Chi, M., & Joram, E. (1995). Assessing students' misclassifications of physics concepts: An ontological basis for conceptual change. *Cognition and Instruction, 13*, 373–400.

Spelke, E. (1991). Physical knowledge in infancy: Reflections on Piaget's theory. In S. Carey & R. Gelman (Eds.), *The epigenesis of mind: Essays in biology and cognition* (pp. 133–169). Hillsdale, NJ: Lawrence Erlbaum.

Spelke, E., Vishton, P., & von Hofsten, C. (1995). Object perception, object-directed action, and physical knowledge in infancy. In M. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 165–179). Cambridge, MA: MIT Press.

Sommers, F. (1959). The ordinary language tree. *Mind*, *68*, 160–185.

Sommers, F. (1965). Predicability. In M. Black (Ed.), *Philosophy in America* (pp. 262–281). Ithaca, NY: Cornell University Press.

Thagard, P. (1992). *Conceptual revolutions.* Princeton, NJ: Princeton University Press.

Westman, R. S. (1975). Three responses to the Copernican theory: Johanne Praetorius, Tycho Brache, and Michael Maestlin. In R. Westman (Ed.), *The Copernican achievement* (pp. 285–345). Berkeley, CA: University of California Press.

Wiser, M., & Carey, S. (1983). When heat and temperature were one. In D. Gentner & A. Stevens (Eds.), *Mental models* (pp. 267–298). Hillsdale, NJ: Lawrence Erlbaum.

Wiser, M., & Amin, T. (2001). Is heat hot? Inducing conceptual change by integrating everyday and scientific perspectives on thermal phenomena. *Learning and Instruction*, *11*, 331–355.