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Why did John Herschel fail to understand polarization? The differences between object and event concepts

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Abstract:

This paper offers a solution to a problem in Herschel studies by drawing on the dynamic frame model for concept representation offered by cognitive psychology. Applying the frame model to represent the conceptual frameworks of the particle and the wave theories, this paper shows that discontinuity between the particle and the wave frameworks consists mainly in the transition from a particle notion 'side' to a wave notion 'phase difference.' By illustrating intraconceptual relations within concepts, the frame representations reveal the ontological differences between these two concepts. 'Side' is an object concept built on spatial relations, but 'phase difference' is an event concept built on temporal relations. The conceptual analyses display a possible cognitive source of Herschel's misconception of polarization. Limited by his experimental works and his philosophical beliefs, Herschel comprehended polarization solely in terms of spatial relations, which prevented him from replacing the object concept 'side' with the event concept 'phase difference,' and eventually resulted in his failure in understanding the wave account of polarization.

Keywords: Herschel; Polarization; Object concept; Event concept; Frame; Cognitive psychology.

1. Introduction

The so-called 'optical revolution,' that is, the disruptive replacement of the particle theory of light by the wave theory of light, occurred in Britain around the early 1830s. In this conceptual change, John Herschel (1792-1871) was a peculiar figure. On the one hand, he had a preference for the wave theory over the particle theory, and he was in fact the 'father' of the wave tradition in Britain by introducing the wave theory to Britain from France through his influential essay 'Light.'[1] On the other hand, 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, particularly, partial polarization. Herschel invented a novel mixture of particle with wave concepts in discussing partial polarization, conceiving partial polarization as the property of a ray that contains an unpolarized and a polarized portion, or as the property of a beam that contains some unpolarized and some polarized rays (Herschel, 1827, p. 509; Buchwald, 1989, pp. 291-96). Neither of these interpretations is consistent with Fresnel's account of polarization.

To adopt a neutral position, one might say that Herschel conceptualized polarization differently from Fresnel. But given the fact that Herschel himself had regarded Fresnel's account of polarization as the best (Herschel, 1827, p. 529), why did he fail to understand this account correctly? Many historians point to the fact that Herschel was deeply influenced by the particle theory that he learned in his early years. Some attribute Herschel's misconception of polarization to his methodological assumption inherited from the particle tradition that all optical phenomena are caused by the action of mechanical forces (Good, 1982). However, it is important to note that the methodological assumption inherited from the particle tradition had also affected Herschel in other subjects of optics. Apparently, Herschel was able to shake off the particle influences in these fields and understood the wave accounts correctly. So, what make polarization special, in terms of the level of difficulty, in the conceptual change from the particle to the wave framework? Why could not Herschel complete the conceptual change by abandoning the particle influences and embracing the wave framework in polarization? In this paper, I suggest that Herschel's misconception of polarization originated from his failure in completing a specific conceptual change by giving up the particle concept 'side' and replacing it with a wave concept 'phase difference.' By drawing on the studies of cognitive psychology, particularly, studies on concept representation, I will further show that 'side' and 'phase difference' are ontologically distinct - the former is an object concept but the latter an event concept. The

[1] Although 'Light' was not published until 1845, it was privately circulated in the British optical community immediately after it was completed. From the spring of 1828, Herschel sent copies of his essay to William Whewell, Thomas Young, David Brewster, George Airy, William Hamilton, and William Fox Talbot: Cantor (1983), p. 162.

ontological differences between these two concepts explain why the transformation from the particle to the wave framework was particularly difficult in polarization.

In this paper, I will develop my historical analyses in the light of the dynamic frame model for concept representation offered by cognitive psychology. I will apply the frame model to represent the conceptual frameworks of the particle and the wave theories. The frame representations will show that discontinuity between the particle and the wave frameworks consists mainly in the transition from a particle notion 'side' to a wave notion 'phase difference.' Both notions were instrumental in accounting for the asymmetric phenomenon of polarization, but the former is an object concept while the latter an event concept. By illustrating intraconceptual relations within concepts, the frame representations will further reveal the ontological differences between these two concepts - the former is built on spatial relations but the latter on temporal relations. The conceptual analyses will display the cognitive source of Herschel's misconception of polarization. Limited by his experimental works and his philosophical beliefs, Herschel comprehended polarization solely in terms of spatial relations, which prevented him from comprehending the temporal nature of polarization, and eventually resulted in his failure in replacing the object concept 'side' with the event concept 'phase difference.'

2. The Particle Framework and Its Representation

Undoubtedly, 'particle' is the most important concept in the particle framework. One way to represent this concept is to define it by a group of atomistic features, such as a set of individually necessary and jointly sufficient conditions. These atomistic features are assumed to be independent components that constitute a single level of analysis, and the relations between them remain implicit. But recent cognitive studies reject this atomistic approach and convincingly argue that some kind of mental structure underlies human cognition. For example, experiments show that information that can be instantiated in a schema is better recalled than information that cannot easily be instantiated in a schema, and subjects with a more developed schema for some body of knowledge show higher recall for materials related to that knowledge (Brewer & Nakamura, 1984). Several models have been developed to capture the underlying mental structures, such as frames (Minsky, 1975), scripts (Schank & Abelson, 1977), schemas (Rumelhart, 1980), mental models (Johnson-Laird, 1980), causal mental models (Gentner & Stevens, 1983), and situation models (van Dijk & Kintsch, 1983).[2] In this paper, I adopt a model of dynamic frames proposed by Larry Barsalou in the 1990s as a cognitive construct to represent concepts (Barsalou, 1992; Barsalou & Hale, 1993).

A frame representation for a concept consists of a set of multi-valued attributes integrated by structural connections. Figure 1 is a partial frame representation for 'particle.' In this frame representation, the superordinate concept 'particle' contains three attributes:

[2] For the differences among these models, see Brewer (1987). For a review of the historical origin of these models, see Brewer (2000).

‘velocity,’ ‘size’ and ‘side.’ Among them, ‘velocity’ and ‘size’ take a continuous value, but ‘side’ takes a dichotomous value. These three attributes represent the basic belief shared by the supporters of the particle tradition that light consists of a sequence of rapidly moving particles susceptible to attractive and repulsive forces defined by the laws of mechanics. Specifically, ‘velocity’ is an attribute that defines the momentum of particles (momentum = mass × velocity). ‘Size’ is an attribute that determines the degree to which particles are susceptible to attractive force according to the second law of Newtonian mechanics. Finally, light is a collective phenomenon, that is, a beam of light consists of a group of particles that either travel together like a bundle or travel one after another as a sequence.[3] To capture this collective aspect, many supporters of the particle tradition, including Newton, assumed that particles have a property called ‘side.’ They believed that the shape of an individual particle is not symmetric. So, a beam of light consisting of a group of particles can have ‘side’ when the particles arrange in an orderly way, but the ‘side’ would disappear when the particles arrange randomly.

Note that the frame divides the properties of ‘particle’ into two groups, attributes and values. All exemplars of ‘particle’ share the properties in the attribute list such as ‘velocity,’ ‘size’ and ‘side,’ but properties in the value list are activated selectively to represent the prototype of a specific subordinate concept. In this way, the frame outlines two kinds of intraconceptual relation. First, it captures hierarchical relations between properties. Contrary to the conventional assumption of all properties within a concept are structurally equal, the frame representation divides properties into two levels. Some are attributes, such as

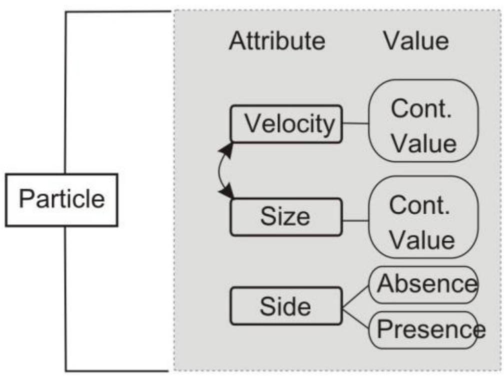

Figure 1. A Partial Frame for Particle

[3] In other words, the collectiveness of light could have either a spatial or a temporal interpretation. Newton never made it clear how he defined rays and beams of light. Many supporters of the particle theory overlooked the possible temporal aspect and defined rays and beams spatially. According to Brewster, for example, a ray of light is the smallest portion of light that remains visible after passing through an aperture: Brewster (1831), p. 12.

‘velocity,’ ‘size’ and ‘side,’ and the rest are values. A value is always attached to a particular attribute and functions as an instance of the attribute. Consequently, not all properties of the superordinate concept are functionally equal: only attributes can be used as classification standards. The second kind of intraconceptual relations appears as horizontal connections between properties. In the frame of ‘particle,’ there is a connection between attributes ‘size’ and ‘velocity.’ This connection, called a structural invariant, imposes constraints to the activations of related values and produce systematic variability in values: when the momentum of a particle is unchanged, an increase of the value of ‘velocity’ requires an decrease of the value of ‘size.’ This structural invarient was instrumental for the particle account of dispersion.

The frame for ‘particle’ also determines the possible concepts at the subordinate level, and thus defines the conceptual field on which various optical phenomena can be understood and explained with the help of laws from mechanics, particularly the laws regarding repulsive or attractive forces. For example, the phenomena of reflection and refraction were frequently explained in terms of the velocity of the particles - particles that travel at a relatively high velocity can penetrate the boundary between two media and thus become refracted; otherwise, they are attracted back to the original medium and become reflected (Newton, 1687, p. 227). Velocity was also used to explain Newton’s rings, this is, concentric interference fringes produced by a convex lens placed on a plane plate. According to Newton, the pattern of bright and dark rings appears because the velocity of some particles is somehow augmented after breaking through the first surface of the convex lens, but the velocity of the others is somehow retarded. Consequently, the retarded particles are reflected by the plane plate and bright rings appear, but the accelerated particles are transmitted through the plane plate and dark rings are seen (Newton, 1952, p. 373).

Similar to ‘velocity,’ the attribute ‘size’ was instrumental in explaining many optical phenomena within the particle framework. For example, Newton offered an explanation of refractive dispersion by assuming that the rays of light consist of particles with different sizes - the violet-making particles are the smallest and least refracted while the red-making ones are the largest and thus refracted most (Newton, 1952, p. 372). Later, Brougham attempted to explain diffraction by assuming that the size of a particle determined not only the degree of inflection, that is, attraction toward the diffracting body, but also the degree of deflection, that is, repulsion away from the body (Brougham, 1796).

Finally, the attribute ‘side’ was critical in understanding such phenomena as double refraction and polarization. Newton felt that it was natural to account for the different paths of the ordinary and extraordinary rays in a doubly refracting crystal by different shapes, or sides, of the particles. He even argued that ‘it’s difficult to conceive how the Rays of Light, unless they be Bodies, can have a permanent Virtue in two of their Sides which is not in their other Sides’ (Newton, 1952, p. 374), using ‘side’ to undermine Huygens’s wave theory, which assumed light to be longitudinal vibrations and thus spatially symmetrical. Later Malus assumed that spatial asymmetry is a fixed feature of every particle, and used it to explain polarization. Specifically, ‘polarized light’ was accounted for by postulating that all particles in a beam of light are arranged in an orderly way, facing the same direction.

‘Unpolarized light,’ or natural light, was understood as randomly arranged rays, facing different directions.

3. The Wave Framework and the Notion of ‘Phase Difference’

Now, let us turn to the conceptual framework of the wave tradition. By the early 19th century, most supporters of the wave tradition believed that light consists of disturbances or waves in an all-pervading elastic medium called ether. To describe the motion of a periodic disturbance, three parameters are needed according to the wave equation: the maximum distance from equilibrium (the amplitude), the velocity of the disturbance, and the distance between two successive identical points in the disturbance (the wavelength).[4] When two periodic disturbances pass through the same region, the resultant motion depends on the relative states of the two disturbances, that is, whether the crest of one disturbance meets the crest of the other, and if not, what is the difference of their phases. Thus, ‘phase difference’ is another parameter to describe periodic disturbances. Figure 2 is a partial frame representation for ‘wave’ according to the wave tradition. In this frame, the superordinate concept ‘wave’ contains four attributes: ‘velocity,’ ‘amplitude,’ ‘ wavelength’ and ‘phase difference.’ Except ‘phase difference,’ all of these attributes take a continuous value.

Similar to the frame of ‘particle,’ the frame of ‘wave’ also offered a conceptual framework for understanding various optical phenomena. For example, refraction is defined

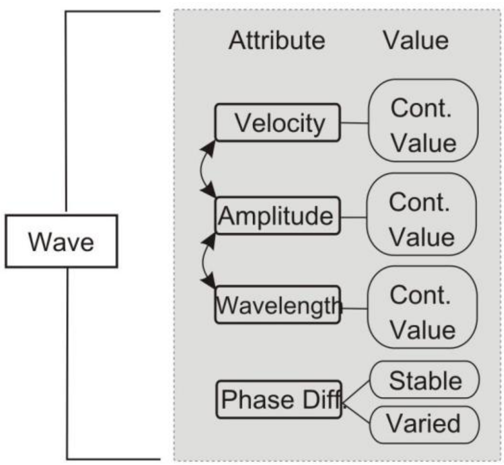

Figure 2. A Partial Frame for Wave

[4] The wave equation for a single periodic disturbance is: $x = A \cos (2 v t / \lambda)$, where A is the amplitude, v the velocity, and λ the wavelength. Sometimes the frequency (f), instead of the velocity and the wavelength, is used in the equation since $f = v/\lambda$.

solely in terms of ‘velocity’ in the wave framework - the index of refraction in a medium is equal to the ratio between the velocity of light in a vacuum and the velocity in the medium. The phenomena of interference and diffraction, which clearly demonstrate the wave character of light and are difficult to understand within the particle framework, become comprehensible with the help of the attributes ‘amplitude,’ ‘wavelength’ and ‘phase difference.’ According to the wave theory, the illumination at a point in a set of fringes caused by interference or diffraction can be determined by the resultant amplitude due to all the wavelets, and the value of the resultant amplitude depends on the phase difference of the wavelets - those wavelets whose phase difference is an even multiple of a half wavelength enhance each other and those whose phase difference is an odd multiple destroy each other.

Finally, ‘amplitude’ and ‘phase difference’ are the keys to comprehend polarization in the wave framework, which defines light as a transverse rather than a longitudinal disturbance. The differences between polarized and unpolarized light consist not in whether any spatial feature exists, because even unpolarized light is always completely asymmetric at any given moment. According to the wave theory, the real differences between polarized and unpolarized light consist in the phase difference and amplitude ratio of the two orthogonal components of a light beam. The orthogonal components of polarized light always have a fixed phase difference and a fixed amplitude ratio, but the phase difference and amplitude ratio of unpolarized light vary over time.

The wave account of polarization was built on a series of experiments conducted independently by Arago and Fresnel around 1816. In the first experiment, Arago put a thin plate of copper with two narrow slits in front of a luminous source (solar light) to produce two unpolarized beams with a common origin. In front of each of the slits, he employed a polarizer (a pile of 15 thin plates of brown glass) that polarized the light almost completely. When the planes of incidence on the two polarizers were parallel to each other, Arago observed the interference fringes as if the light beams were in their natural state. But when Arago turned one of the polarizers around until its plane of incidence was perpendicular to that of the other, the interference fringes vanished.

If the precondition for two polarized beams to interfere is that their planes of polarization are not perpendicular to each other, interference fringes could be restored in Arago’s second experiment when the polarization plane of one of the beams was altered. To examine this possibility, Arago conducted a third experiment. Beginning with the setting in which the planes of the two polarized beams were perpendicular to each other, he put a doubly refracting crystal behind one of the polarizer, with its principal section 45 degrees inclined to the polarization plane. Light emerging from the crystal was divided into two beams with planes of polarization that were no longer perpendicular to the beam from the other polarizer. Under this circumstance, interference fringes should reappear, Arago reasoned. Yet no fringes were seen.

A few years later Fresnel altered the setting and conducted a fourth experiment. He used a beam of polarized light as the source, and put a doubly refracting crystal (a gypsum lamina) in front of the double slits. The crystal produced four beams of light, two from each slit, with planes of polarization perpendicular to each other. Fresnel then used a doubly refracting prism to alter these beams' planes of polarization and made them parallel to each other. This time, as expected, he saw fringes of interference: the resulting fringe patterns showed that all the ordinary rays from the prism interfere with each other, and all the extraordinary rays also interfere with each other (Herschel, 1827, p. 531).

The third and the fourth experiment were puzzling. Since Huygens, wave theorists had always conceptualized waves as longitudinal vibrations, which were spatially symmetric. To account for polarization, an asymmetric phenomenon, transverse vibrations must be added into the picture, and waves were defined as the resultant of both longitudinal and transverse vibrations. Specifically, unpolarized light either is completely longitudinal or contains equal transverse vibrations all around its ray, and polarized light does not contain a longitudinal component and is completely transverse. In other words, polarization was defined merely in terms of spatial asymmetry. According to this interpretation, interference fringes should have appeared in the third experiment, because the polarization planes of the two beams of light emitted from the two slits were not perpendicular to each other, and both of them originated from the same source and thus were coherent. Furthermore, changing the source from natural to polarized light in the fourth experiment should not have caused any difference, because orderly arrangement of the spatial asymmetry in polarized light did not alter any precondition for interference.

To solve the puzzle, Fresnel proposed a new wave model between 1819 and 1821: light contains only transverse vibrations (Buchwald, 1989, pp. 226-31). According to Fresnel, even natural light was always completely asymmetric - it contains the rapid succession of waves polarized in all directions. The differences between polarized and unpolarized light consist in the phase difference and amplitude ratio of the two orthogonal components of a light beam. The orthogonal components of polarized light always have a fixed phase difference and a fixed amplitude ratio, while the phase difference and amplitude ratio of unpolarized light vary over time. In other words, polarization was defined in terms of a temporal process. The state of phase difference over time is the key to understand Arago's and Fresnel's experiments on interference of polarized light. In the third experiment, light beams emerging from the two polarizers came from the perpendicular components of the unpolarized source. Since the phase difference between the orthogonal components varied over time in unpolarized light, these two light beams were incoherent and thus no interference occurred. The use of a polarized source in the fourth experiment altered the condition of coherence. Since the phase difference between the orthogonal components was fixed in polarized light, light beams derived from the perpendicular components of the polarized source were coherent, and consequently interference fringes appeared.

4. The Ontological Differences between 'Side' and 'Phase Difference'

The frame representations of 'particle' and 'wave' offer a powerful means to analyze the conceptual change during the optical revolution. By comparing the frames of 'particle' and 'wave,' particularly the two attribute lists, we can clearly see the similarities and differences between the two conceptual frameworks. Evidently, not all attributes from the frame of 'particle' were abandoned during the conceptual change. Some attributes from the old frame were preserved, and some others were deleted. At the same time, new attributes were added to the frame of 'wave' and many attributes from the old frame were rearranged in different ways. Through analyzing the continuity and discontinuity between the two frames, we can have a better understanding of the conceptual change - in particular, how difficult it was for someone to undertake such a conceptual change and how difficult it was for people from different traditions to understand each other. More importantly, by analyzing the attribute lists, we can identify the sources of incommensurability during this conceptual change by asking such questions as which elements in the frames were responsible for the misconception that some historical figures developed and why these elements were difficult to comprehend.

'Velocity' is the only attribute shared by the frame of 'particle' and the frame of 'wave.' The particle and the wave theories defined 'velocity' in the same way, as a parameter that measures the rapidity or swiftness of a physical motion, even though they understood the object of the physical motion differently. Both theories made similar claims that the velocity of light is not related to the intensity of the source and it remains constant in a homogeneous medium, although one of them (the particle theory) assumed that the velocity of light is greater in a denser medium while the other implied the opposite. Nevertheless, 'velocity' is the continuous element between the two conceptual frameworks. Followers of the two optical traditions should be able to understand each other when they discuss this notion, and it is unlikely, if not impossible, that miscommunication or incommensurability would be caused by this notion.

Another continuous link consists in the relations between attribute 'size' in the frame of 'particle' and attributes 'amplitude' and 'wavelength' in the frame of 'wave.' In the particle framework, 'size' serves two functions. On the one hand, 'size' defines intensity or brightness - when traveling at the same velocity, particles with larger size (i.e. larger mass) carry greater momentum and consequently produce brighter sensations. On the other hand, 'size' also defines colors - particles with different sizes are subject to different degrees of force, either attractive or repulsive, and subsequently have different refrangibilities. In the wave framework, the meanings of 'intensity of light' and 'color of light' remain the same, but they are defined by two attributes: 'amplitude' for the intensity and 'wavelength' for the color. Thus, it is also unlikely that the split of an old attribute could cause any significant miscommunication between the two camps.

The fundamental difference and the discontinuity between the two optical theories consist in the deletion of 'side' from the frame of 'particle' and the addition of 'phase difference' to the frame of 'wave.' They are two ontologically distinct concepts. One the one hand, 'side' is an object concept, referring to instances that occupy space and are definable by boundaries. In his research on the underlying basis of concepts, Lakoff suggests that image-schemas lie at the core of object concepts. Image-schemas are schematic, spatial images that constantly recur either in our everyday bodily experience or in various orientations and relations. Examples of image-schemas include CONTAINER, PATHS,

FORCES, UP-DOWN, FRONT-BACK, PART-WHOLE, and CENTER-PERIPHERY, all of which are directly derived from perceptual experiences of spatial structures (Lakoff, 1987, p. 267). For example, based on our daily experience that our bodies are both containers and things in containers (e.g. rooms), we develop a CONTAINER schema that consists of a simply spatial structure - a boundary distinguishing an interior from an exterior. Conceptualization of taxonomic categories or object concepts involves a process of 'spatialization,' in which image-schemas are used to map metaphorically the spatial structures of physical space into a conceptual space. For example, to conceptualize 'side,' a CONTAINER schema is needed, which offers a spatial structure to identify orientations. In this way, 'side' is built upon our perceptual experiences of various spatial relations. In general, representing object concepts involves a process of conceptual partitioning, in which the mind extends a boundary around a portion of what would otherwise be a continuum of space, and ascribes to the contents within the boundary the property of being a single-unit entity. In such a partitioning process, contents that are perceptually salient, such as those having a clear boundary or those identifiable by shape, would be identified and ascribed quickly and frequently. In other words, the mind tends to represent object concepts in a certain way by preferring attributes that contain salient spatial information and thus offer more diagnostic cues than others.[5]

Unlike object concepts, 'phase difference,' that is, the relative states of the orthogonal parts of a disturbance, is an event concept, describing instances that have no volume and are not definable by boundaries. Instead, it represents sequences of activities or series of incidents that always have a beginning and an end and always vary with time. It has been suggested that event concepts are ontologically distinct from object concepts (Sommers, 1971; Keil, 1979; Chi, 1992). A common method to detect the differences between object and event concepts is to examine the predicates. Predicates that modify object concepts cannot be applied to event concepts, nor the other way around. For example, an object designated by 'side' has the potential to be facing east even though it may not be, whereas an instance of 'phase difference' cannot be facing east. Conversely, a 'phase difference' can be stable but a 'side' cannot.

The differences between object and event concepts are not merely linguistic. Barsalou and Sewell had conducted a series of experiments in which they first asked subjects to generate examples of a series of event concepts such as 'writing a letter,' 'doing the laundry' and 'going grocery shopping' under unconstrained condition, and then they asked the subjects to generate examples of these concepts in a specific order, from most to least typical. If event concepts are represented the same way as object concepts, explicitly instructing subjects to retrieve examples of actions in this manner should not decrease the rate of production, because studies have shown that exemplars of object concepts are retrieved according to their typicality - those similar to the prototypes of the superordinates are generated easily and quickly. But the performance of the subjects in these experiments

[5] Experimental studies from cognitive psychology confirm that people indeed prefer attributes that contain rich spatial information when they represent object concepts; see Rosch, et al. (1976) and Tversky & Hemenway (1984).

was affected when they were instructed to retrieve examples of actions from most to least typical. Later, Barsalou and Sewell asked the subjects to generate examples of these event concepts according to a temporal sequence, first in the forward condition, that is, from the first action of the sequence to the last, and then in the backward condition, that is, from the last to the first action in the sequence. Again, if event concepts are represented the same way as object concepts, there should not be any difference under these two circumstances - studies have shown that generating examples from object concepts according to size is always difficult regardless of whether exemplars were produced from the smallest to the largest or from the largest to the smallest. However, Barsalou and Sewell found that subjects generated more examples in the forward condition than in the backward condition. In fact, the subjects had the best performance when actions were generated in the forward condition, that is, in their normal temporal sequence (Barsalou & Sewell, 1985).

Barsalou and Sewell's experiments indicate that there are different retrieval patterns between object and event concepts. The differences in the retrieval pattern, specifically, in the rate of production, reflect significant differences in the underlying mental organizations and cognitive processes, because the fastest rate of production should be the one in which the underlying organization is followed as directly as possible (Barsalou & Sewell, 1985, p. 651). Thus, Barsalou and Sewell believe that event concepts are dimensionally organized in memory, that is, their components are chained together in memory according to increasing or decreasing values on some dimension, which explains why during the experiments the retrievals of event concepts were fast when they took advantage of these dimensional orders.

In terms of their representations, event concepts are distinctively different from object concepts. Unlike object concepts in which intraconceptual relations are spatial, an event concept such as 'doing laundry' is built primarily upon a routine series of incidents, or some kind of temporal relations. Many cognitive scientists use scripts to capture these temporal relations. A script is a knowledge structure that specifies the conditions and actions for achieving a goal. Consider the script of 'doing laundry.' This script specifies the initial conditions that must be met if the goal is to be achieved; for example, dirty clothes exist, a washer and dryer are available, and laundry detergent is present. The script further specifies the sequence of actions that will achieve the goal, for example, collecting dirty clothes, turning on the washer, placing detergent in the washer and putting clothes in the washer (Barsalou, 1992, p. 76). There is strong evidence for scripts in goal-derived activities. Memory experiments show that actions that are parts of a script are better recalled than other actions. When people are presented with script actions in the wrong order, they rearrange them to their typical order during recall even after being instructed to recall them in their presented order (Bower, et al., 1979).

Event concepts can also be represented by frames. Figure 3 is a partial frame representation of 'phase difference' according to the wave tradition. To capture the meaning of 'phase difference,' two specific frames are needed. On the left-hand side is a frame representing the orthogonal components of a light beam - its attributes represent the orthogonal parts of a disturbance ('vector 1' and 'vector 2') and the values of these attributes describe specific states, or specific phases, of the vectors. On the right-hand side

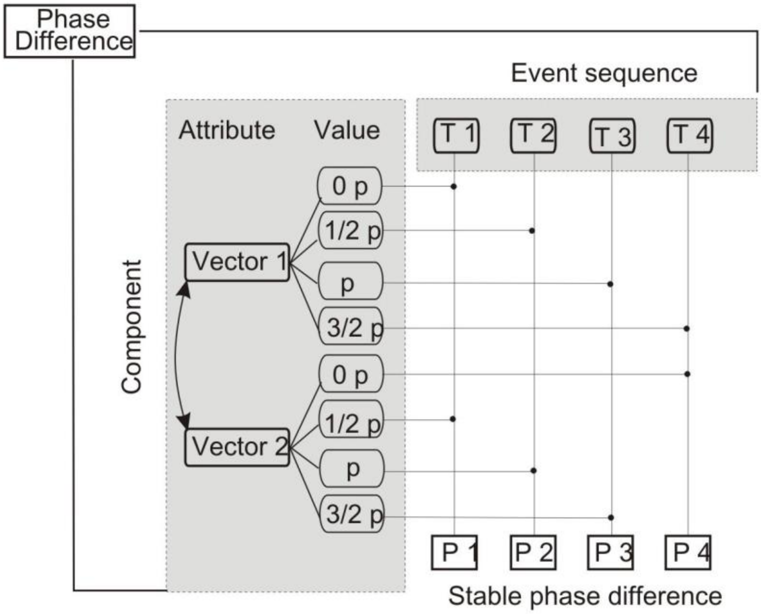

Figure 3. A Partial Frame for Phase Difference

is a frame that captures an event sequence. The attributes in this frame (only four are listed for the sake of simplicity) represent different moments in the sequence, each of which takes specific value corresponding to an attribute in the component frame. For example, 'T1' is the moment when 'vector 1' is '0π' and 'vector 2' is '½ π,' 'T2' is the moment when 'vector 1' is '½ π' and 'vector 2' is 'π,' and so on. By connecting all of these moments, we obtain a sequence of subordinate concepts: 'phase difference at T1,' 'phase difference at T2' and so on, which collectively represent an event, 'stable phase difference.' Obviously, these subordinates are parts but not examples of the superordinate 'phase difference.' Thus, an example of 'stable phase difference' cannot be generated according to its relations to the superordinate category. Instead, to apply the notion 'stable phase difference' requires following a normal temporal sequence, and more specifically, requires observations over time.

There are also differences between object and event concepts in conceptual relations. Evidently, the frame of an event concept does not generate a taxonomy. The subordinate concepts in Figure 3 are not examples of the superordinate concept. Instead, they are parts of 'phase difference.' In other words, the intraconceptual relations of an event concept produce a partonomy built upon part-whole relations, rather than a taxonomy built upon inclusive and contrast relations. Furthermore, subordinate concepts in Figure 3 are no longer independent. They are related directly to each other through causal links - 'phase 1' physically causes 'phase 2' and so on.

An even more important difference between object and event concepts is the nature of the intraconceptual relations. Similar to object concepts, representing event concepts involves a process of conceptual partitioning, in which the mind extends a boundary around a portion of what would otherwise be a continuum of time. But unlike object concepts in which the partitioned space is circumscribed by properties (attributes), the ascribed time in event concepts is represented by an event sequence. When the mind represents, memorizes, and retrieves event concepts, it apparently adopts an approach different from that for object concepts. Specifically, it seems that the mind does not represent temporal relations by properties, but by dimensional organizations of temporal sequence. Barsalou and Sewell's experiments seem to support this speculation. Thus, object and event concepts are treated by the mind differently in representation, memory, and retrieval.

How concepts are represented, memorized and retrieved by the mind directly affects how they are learned, which is the core of conceptual change. If a transformation occurs between concepts that belong to the same ontological category, the learning process could be smooth. The old concept can be used as a guide for the acquisition of the new one; more specifically, the frame of the old concept can be used as a pattern to form a new frame for the new concept. A variety of learning techniques, such as addition, deletion, discrimination, generalization, concatenation, chunking and analogizing, can be used to transform an old concept into a new one in a piecemeal manner. Many important conceptual changes, such as the one from the Aristotelian 'physical object' to the Newtonian 'astronomical object' during the Copernican revolution were probably achieved in this way (Chen & Barker, 2000). However, if a transformation requires crossing concepts that belong to different ontological categories, acquisition of a new concept must proceed by teaching it independently of the old conceptual framework. Because of their distinct structures, the old concept is usually not merely useless, but also misleading. Hence, from a cognitive point of view, such a learning process could be very difficult, if not entirely impossible (Chi, 1992). It is difficult to accomplish a conceptual change from an object concept to an event concept or vice versa. Particularly, it is reasonable to expect that the differences between 'side' and 'phase difference,' an object and an event concept, can cause communication problems or incommensurability during conceptual change.

5. The Cognitive Sources of Herschel's Misunderstanding

Herschel began his studies of polarization in the late 1810s. In an article published in 1820, Herschel reported his extensive research on colored rings produced by crystal plates with polarized light, known as the phenomenon of chromatic polarization (Good, 1982). Arago first observed colored rings in 1811 by using a prism of Iceland Spar to examine a very thin lamina of mica under a skylight that, he later realized, was polarized. After that, Biot, Brewster and Fresnel also conducted experiments to study the colored rings produced by crystal plates when exposed to polarized light. In many ways, Herschel's understanding of polarization was deeply influenced by Biot's work.

In Biot's experiments on chromatic polarization, a beam of light, first polarized by reflection from a plate of glass (the polarizer), was transmitted through a doubly refracting crystal, and then reflected again at the angle of polarization by another plate of glass (the analyzer), whose plane of reflection was at right angles to the polarizer. Without the doubly refracting crystal, no light was transmitted after the two reflections. But when the doubly refracting crystal was inserted between the two plates of glass, a pattern of colors similar to Newton's rings appeared. At first glance, the appearance of the tints was accounted for by the existing particle framework equipped with the spatial notion 'side.' Without the crystal, all particles are transmitted through the analyzer because their plane of polarization is perpendicular to its plane of reflection. When the crystal is inserted, it creates two beams of light with planes of polarization that are no longer perpendicular to the plane of reflection of the analyzer. Thus, some particles are reflected by the analyzer and a pattern of colors appears.

But Biot soon realized that the existing particle notion 'side' could not explain every detail of his experiments. When rotating the doubly refracting crystal, Biot found that the intensity of the tints changed accordingly, but the pattern of the tints remained the same. These contradicted the existing particle account, which predicted that rotating the crystal should alter the planes of polarization of the ordinary and the extraordinary ray, and consequently the pattern of the tints. Biot further found that, in uniaxial crystals, the pattern of the tints was determined solely by the length of the path traversed by the light within the crystal, which again was inexplicable according to the existing particle framework. To explain these newly found phenomena, Biot introduced a theory of 'mobile polarization' by adding an oscillation assumption. According to Biot, when a polarized ray enters a crystal, some particles begin a series of oscillations around their centers of gravity. Their planes of polarization alter alternately to one side or other of the axis of the crystal. The period of the oscillation is analogous to the length of fit in Newton's rings, determined solely by the nature of the particles (the color of the ray). The oscillatory movement is supposed to stop when the particles emerge from the crystal to the air, and the plane of polarization of the emergent ray is determined by the last oscillation of the particles at the instant of emergence. Hence, rotating the crystal does not alter the plane of polarization at the instance of emergence, and the thickness, not the angular position, of the crystal determines the pattern of the tints (Buchwald, 1989, pp. 86-107).

Because of the oscillation assumption, Biot no longer understood 'side' as a fixed character of particles; instead, a particle of light can alter its 'side' due to the impact of physical forces exerted from the crystal. Figure 4 is a frame representation of Biot's notion of 'side.' It contains two attributes: 'asymmetry' and 'oscillation' - the former describes the initial plane of polarization when the ray enters the crystal, and the latter specifies the degree of change in the plane of polarization when the ray passes through the crystal. Each attribute can take a continuous angular value between 0 to 360 degrees. With information regarding the thickness of the crystal, the frame determines the plane of polarization received by the analyzer. Evidently, the attribute 'oscillation' does not alter the spatial nature of 'side.' What mattered to Biot was not the processes of the oscillations, but the

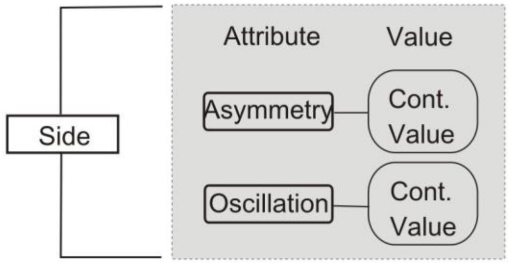

Figure 4. A Partial Frame for Biots Side

spatial asymmetry of the particles at the instant when they emerged from the crystal. Biot used the oscillation assumption as an ad hoc mechanism to manipulate the spatial character of particles.

Herschel learned the outline of Biot's theory of mobile polarization in 1818, and he understood some of its details after he visited Biot in 1819. Later, he offered a rather accurate summary of Biot's theory, calling it 'a hypothesis of a force inherent in its molecules independent of their state of aggregation, by which they communicate a rotation in an invariable direction to the axes of polarization of the luminous rays' (Herschel, 1820, p. 62). Herschel also conducted a series of experiments on tourmaline to test Biot's theory. These experiments confirmed Biot's observations that the pattern of the tints depends only on the thickness, not the angular position, of the crystal. Thus, Herschel became convinced and he stated that Biot's hypothesis 'is partially supported by the fact, that the tint developed along the axis, descends in the scale of colour as the thickness increase' (Herschel, 1820, p. 62).

Around mid 1818, Brewster's experimental investigation of chromatic polarization by biaxial crystals also caused Herschel's attention. He soon conducted a series of experiments to study the pattern of tints in biaxial crystals. The setting of Herschel's experiments was very similar to that of Biot's except two differences. First, Herschel used plates of tourmaline, instead of reflecting glasses, as the polarizer and analyzer. A plate of tourmaline with moderate thickness can produce highly polarized light, and no light can pass two plates of tourmaline with their optic axes perpendicular to each other. Second, unlike Biot who observed the tints by bringing the eye close to the analyzer, Herschel designed a new instrument to project the colored rings onto a screen about three inches behind the analyzer. This method allowed Herschel to examine the details of the tints (Herschel, 1820, pp. 96-100).

Herschel carefully recorded the tints produced by several biaxial crystals, such as sulphate of baryta (barium sulfate) and Rochelle salt (potassium sodium tartrate). He reported that, unlike the tints of uniaxial crystals that consisted of a series of concentric circles, the tints of biaxial crystals had a general resemblance to the figure 8 (the form of lemniscate) with two poles, corresponding to the two axes of the crystals. Following Biot, Herschel believed that each bright band in the tints represented a locus of directions in the crystal over which all the particles underwent the same number of oscillations. He also found that the lemniscates were explicable by the number of the oscillations of the particles, or the magnitude of the polarizing force that caused the oscillations, both of which were assumed to be proportional to the distances to the optic axes of the crystal. However, additional examinations of the tints of biaxial crystals revealed several significant deviations from Biot's theory. The most important one was that colored tints (greenish blue and yellowish pink) appeared in the poles of the lemniscates. This directly contradicted Biot's theory. According to Biot, the poles of the lemniscates should be completely black, because in the directions of the axes, no polarizing forces would act on the particles, and the particles do not oscillate. Thus, particles traveling along the axes should maintain their initial plane of polarization and cannot be picked up by the analyzer.

At first, Herschel attributed the deviations to the imperfect shape of the crystals, but soon he realized that the deviations had nothing to do with the shape of the crystals, and that they really posted 'a radical and unanswerable objection' to the theory of Biot. Herschel never intended to give up Biot's theory; instead, he tried to save it by introducing an ad hoc assumption. To explain the colored poles in the tints of biaxial crystals, Herschel found that he must revise Biot's original theory, in particular, Biot's implicit assumption that the directions of double refraction are independent of the nature of the particles, so that particles of different colors travel along the same direction, that is, either the direction of the ordinary ray or that of the extraordinary ray. Herschel introduced a color-dependence assumption, claiming that 'the axes of double refraction differ in their position in the same crystal for the differently coloured rays of the spectrum, being dispersed in one plane over an angle more or less considerable, according to the nature of the substance' (Herschel, 1820, pp. 49-50). If particles of different colors travel in different directions in biaxial crystals, then many of them will have axes of double refraction different from the directions corresponding to the poles of the lemniscates. Along these directions, many particles will be affected by polarizing forces and engaged in oscillations. Consequently, the poles should not be black but tinted.

Figure 5 is a frame representation of Herschel' notion of 'side.' Its only difference from

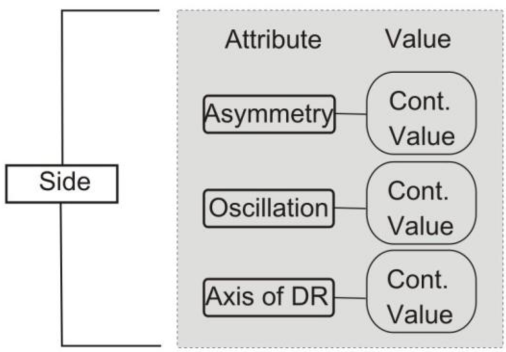

Figure 5. A Partial Frame for Herschels Side

Figure 4, Biot's notion of 'side,' is that it contains one more attribute: 'axis of double refraction.' This attribute describes the directions of the doubly refracted rays, and takes a continuous angular value from a small range determined by the nature of the crystal. With information regarding the degree of the dispersion of the axes, the frame can adjust the plane of polarization received by the analyzer to make it consistent with the observation. Thus, the new attribute 'axis of doable refraction' does not alter the spatial nature of the notion. Again, Herschel used this additional assumption as another ad hoc mechanism to manipulate the spatial character of particles.

The ontological difference between 'side' and 'phase difference' explains why Herschel failed to understand polarization but not other optical phenomena. Because they are ontologically distinct, the conceptual change from 'side' to 'phase difference,' necessary for the transformation from the particle account to the wave account of polarization, cannot be achieved in a piecemeal manner. The old concept 'side' must be abandoned before the new concept 'phase difference' can be comprehended. But limited by his own experimental works, Herschel never gave up the spatial notion 'side.' He continued to use spatial asymmetry to explain his experiments, and thus he was never able to understand polarization as a temporal process, the key for the wave account of the phenomenon.

The consequences of Herschel's failure in completing the conceptual change from 'side' to 'phase difference' become evident in his essay 'Light,' in which he reviewed Arago's and Fresnel's experiments on interference by polarized light, but evidently did not capture the notion of polarization that emerged from the experiments. When Herschel introduced Fresnel's theory of polarization, he emphasized a particular aspect of Fresnel's theory, that is, that waves are transverse vibrations. He wrote: 'According to [Fresnel's] doctrine, a polarized ray is one in which the vibration is constantly performed in one plane' (Herschel, 1827, p. 534). But it seems that Herschel did not comprehend a critical issue of Fresnel's theory of polarization, that is, polarization requires a stable phase difference between the two orthogonal components. By using the direction of vibrations, an equivalence of 'side,' to define polarization, Herschel grasped only a special kind of polarization - plane-polarized light, in which the orthogonal components have no phase difference and thus can be regarded as performing vibrations in the same plane.[6] Herschel's notion of unpolarized light was also mistaken. Herschel wrote that 'an unpolarized ray may be regarded as one in which the plane of vibration is perpetually varying, . . . ' (Herschel, 1827, p. 534). Again, Herschel attempted to define unpolarized light in terms of the direction of vibrations. Without the notion of phase difference, Herschel would never be able to comprehend the nature of unpolarized light. On another occasion, he stated that 'an ordinary or unpolarized ray may be regarded as composed of two polarized rays, of equal intensity, having their planes of polarization at right angles to each other (Herschel, 1827, p. 509). This is simply wrong - according to the wave theory, if a light beam can be discomposed into two

[6] There are two more states of polarization: circular polarization is a state in which the orthogonal components have a phase difference of 90 degrees but no difference in their amplitude, and all other possibilities fell into the category of elliptic polarization.

orthogonal vibrations with a stable phase difference and an equal amplitude, it is a circular-polarized light!

Without distinguishing polarized and unpolarized light in terms of phase difference, Herschel experienced difficulties in accounting for Arago's and Fresnel's experiments. The first two experiments done by Arago were relatively easy for Herschel to explain. He believed that he could account for the different results between these two experiments by simply appealing to the orientation of polarization. In the first experiment, the planes of polarization of the interfering rays had the same orientation, and interference fringes thus appeared. In the second experiment, interference fringes disappeared, and 'their absence, then, must be owing to the opposite state of polarization of the interfering rays' (Herschel, 1827, p. 530).

The last two experiments, however, were far more difficult. Herschel again attempted to explain the appearance of interference fringes in the fourth experiment by Fresnel in terms of the orientation of polarization. He claimed that in this experiment, 'as each ray of these pairs respectively have similar polarization, ... there is no reason why interference should not take place' (Herschel, 1827, p. 532). But he immediately realized the problem - interference fringes should have appeared in the third experiment because some rays there also had similar orientation of polarization. Thus, Herschel admitted that 'the difficulty remained to explain, not why colours were produced in certain circumstances, but why they were not produced in all, in short, what share the polarization of the incident, and the analysis of the emergent rays, had in the production of the phenomena' (Herschel, 1827, p. 532).

According to the wave theory, there is no interference in this experiment because rays derived from the perpendicular components of the unpolarized source have unstable phase differences. Herschel however did not understand the notion of 'phase difference,' and the only explanatory tool that he had was the spatial notion 'side,' or 'orientation of polarization.' Since Herschel defined unpolarized light as composing of two polarized rays at right angles to each other, he developed an account for the third experiment in terms of the spatial differences related to the two orthogonal components of unpolarized light. Herschel reasoned that 'this case ... is the same with that of a ray consisting of two equal rays oppositely polarized, and therefore in each pencil will coexist, superposed on each other, the primary and complementary colour arising from either portion, which being of equal intensity will neutralize each other's colours and the emergent pencil will be white, and each of half the intensity of the incident beams. This then is the reason ... why we see no colours when the light originally incident on the crystallized plate is unpolarized' (Herschel, 1827, p. 533). In essence, Herschel tried to explain the disappearance of interference fringes by assuming that the two orthogonal components generated two sets of interference rings but they canceled each other and thus no fringes were visible.

Limited by the spatial notion of 'side' embedded in his own polarization experiments, Herschel did not understand the wave account of polarization that requires a temporal notion of 'phase difference.' Herschel was confused when he tried to interpret the meaning and the nature of polarization, and his remarks on polarization were incoherent, consistent neither with the newly emerged wave framework, nor with the traditional one. This confusion made it impossible for him to explore the implications from Fresnel's notion of polarization, in particular, the taxonomies associated with Fresnel's notion. For example, Fresnel's notion suggests a dichotomous classification of polarization, that is, light is either polarized or unpolarized, and the old concept of 'partial polarization' must be abandoned. But Herschel continued to adopt the notion of 'partial polarization,' claiming that 'a beam composed of many coincident rays may be partially polarized, inasmuch as some of its component rays only may be polarized, and the rest not so. This distinction once understood, however, we shall continue to speak of a ray as wholly or partially polarized, in conformity with common language' (Herschel, 1827, p. 509; original emphasis).

Fresnel's notion of polarization also suggests a dichotomous classification of light, that is, all optical phenomena must be first classified solely in terms of their states of polarization, because the state of polarization reflects the nature of light - transverse vibrations - and it thus determines other optical properties such as the direction and the amplitude of a vibration. Dichotomous classification of light was later developed by Lloyd and widely accepted by the wave community. Such a dichotomous taxonomy was crucial in the particle-wave debate, because many explanatory merits of the wave theory were amplified to a maximum in the dichotomous system (Chen, 1995). Herschel however did not appreciate the possibility of classifying all optical phenomena dichotomously. In 'Light,' he adopted a taxonomy that classified optical phenomena into four categories. Many defects of the wave theory, such as its failure in explaining dispersion, were highlighted in Herschel's taxonomy. Consequently, when Herschel evaluated the two rival theories of light under his taxonomy, he developed a preference for the wave theory, but he was reluctant to embrace it completely. At the same time, the explanatory success of the particle theory in dispersion and absorption, which represented two important categories in Herschel's taxonomy, led him to hold that the particle theory was still valuable. Thus, in a rather long period after he established his preference for the wave theory, Herschel did not believe that the particle theory should be totally abandoned. Instead, he suggested that the particle theory should be improved: '[I]t is by no means impossible that the Newtonian theory of light, if cultivated with equal diligence with the Huyghenian, might lead to an equally plausible explanation of phenomena now regarded as beyond its reach' (Herschel, 1831, p. 262).

6. Conclusion

The cognitive analysis presented above reveals a possible source of Herschel's misconception of polarization. With the help of the frame account for concept representation, we recognize the ontological differences between object and event concepts: intraconceptual relations in object concepts are in essence spatial, but those in event concepts are temporal. Cognitive studies further indicate that the mind treats object and event concepts differently in representation, memory and retrieval. Thus, transitions from object concepts to event concepts involve radical change that is extremely difficult, if not impossible, to achieve. Furthermore, our analyses of the conceptual frameworks of the two rival optical theories indicate that a radical transformation crossing different ontological categories is necessary for completing the conceptual change. Specifically, the transformation from a particle concept of polarization to a wave concept of polarization requires abandoning the old object concept 'side' and replacing it with a new event concept 'phase difference.' Finally, through examining Herschel's experimental works on chromatic polarization, we discover that Herschel's understanding of polarization was built on Biot's theory of mobile polarization, and he continued to use 'side' to account for polarization. Because he committed himself to this object concept, Herschel never acquired the notion of 'phase difference' that was necessary to comprehend the wave account of polarization, and he continued to use 'side' to account for Arago's and Fresnel's experiments on polarization. Thus, failing to complete the transition from an object concept 'side' to an event concept 'phase difference' might have caused Herschel's misconception of polarization.

Herschel's failure in completing the conceptual change from 'side' to 'phase difference' can be further accounted for in the terms of the cultural and philosophical traditions in which he was trained. To appreciate Fresnel's temporal treatment of polarization required a new tool of analysis to replace the existing notion 'ray' for conceptualizing optical phenomena (Buchwald, 1989, pp. xiv-xviii). According to Fresnel, polarization refers to the asymmetry at a given instant and at a given point in the wave front. Since one can always draw a line to connect any given point in the wave front to the center of the wave and label it a ray, it makes sense to discuss the state of symmetry of a ray within the wave framework. But if 'ray' is understood as a physical representation that refers to the moving path of a particle or a wave, to say that a single ray is polarized or, especially, to say a single ray is unpolarized, is absolutely absurd because each ray is always spatially asymmetrical. Thus, to understand Fresnel, it becomes necessary to treat 'ray' merely as a mathematical abstraction rather than as a physical representation, and to give it up as a basic analytic model. Evidently, Herschel continued to treat 'ray' as a physical representation. For example, he did not know that Fresnel's method of orthogonal decomposition is just a mathematical analysis for computational purposes, and mistakenly believed that he could use an experimental procedure to decompose a ray of light into two orthogonal vibrations (Herschel, 1827, p. 509). Why did not Herschel master the new tool of analysis developed by Fresnel? It is unlikely that Herschel did not have the necessary mathematical skills to understand the mathematical nature of 'ray.' Herschel was quite sophisticated mathematically, and he was one of the founding members of the Analytical Society at Cambridge that promoted the replacement of the Newtonian geometrical method by the French differential calculus. It is more likely that Herschel did not have an adequate methodology or philosophy to entertain the possibility that 'ray' could simply be a mathematical abstraction. Influenced by the Newtonian notion of 'verae causae,' Herschel believed that the goal of science was to portray the unobservable things and events that produced observed phenomena. These unobservable things and events are 'true causes' because they have 'a real existence in nature, and not being mere hypotheses or figments of the mind' (Herschel, 1831, pp. 144).

Given this strong realist interpretation, it could be rather difficult for Herschel to imagine 'ray' as a pure mathematical abstraction.[7]

In addition to solving a problem in Herschel studies, our cognitive analysis also sheds light on the nature of the optical revolution. Most existing accounts characterize this historical event as a transition in explanatory model: from light as particles to light as waves. But the transition from 'particle' to 'wave' could be superficial, if 'wave' was treated as an object concept, that is, as vibrations defined merely by spatial differences. Cognitive studies have found that conceptual change between concepts with the same ontological status, say, from an object to another object concept, is evolutionary, and can be achieved through a series of non-revolutionary approaches such as revising part-whole relations and rearranging existing categories (Chi, 1992, pp. 167-78). So it was not too difficult for some practitioners of the old optical tradition to conceive 'wave' in terms of spatial differences and to add features describing spatial vibrations into their notions of 'particle.' For example, Brewster readily accepted a definition of polarized light in terms of two orthogonal vibrations, and he even adopted the notion 'phase' from Fresnel but he interpreted it simply as a parameter that describes a spatial feature of a vibration (Brewster, 1830; Buchwald, 1989, pp. 404-08). On the other hand, the transition from 'side' to 'phase difference' involves a conceptual change across different ontological categories, from spatial to temporal. This kind of conceptual change is bound to be disruptive, and frequently results in confusion and misunderstanding among those who experience the revolutionary transition. Thus, to capture the revolutionary nature of this historical event, and to comprehend the degree of difficulties involved in this conceptual change, we must also characterize the historical event as a transition in conceptual representation: from light as a spatial object to light as a temporal process.

How the optical revolution should be defined is not a trivial question, but reflects some fundamental differences in historiography. The preference for explanatory models in many existing accounts of the optical revolution is rooted in the traditional philosophy of science, specifically, the positivist account of science that highly values the importance of explanation. But explanation is only one aspect of scientific practice - it mainly reflects applications of scientific theories occurring after the learning process. Before explanation, the subjects to be studied need to be explored through experiments, represented by concepts, investigated with the help of analytic tools, and organized into a classification system. All of these are equally important to scientific practice. Thus, the optical revolution should be characterized in a multi-dimension manner. It indeed contained a transformation of explanatory model, from light as particles to light as waves, but it also involved many other transformations at different cognitive levels. For example, there was a fundamental transformation in the classification system, from the traditional taxonomy that classified optical phenomena into eight categories to a dichotomous system (Chen, 1995), there was a

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7 Herschel's view on true causes can be placed in the context of the Newtonian-Cartesian conflict: Wilson (1974). It will need a full-blown research project to examine the connections between Herschel's attitude toward mathematical abstractions and the Newtonian-Cartesian conflict.

profound change in the analytic tool, from treating ‘ray,’ the unit of optical analysis, as a physical object to a mathematical construct (Buchwald, 1989), and there was a notable modification in the style of experimentation, from regarding the eye as an ideal optical instrument to reducing the role of the eye in optical experiments (Chen, 2000). By analyzing the optical revolution at the level of concept representation and focusing on the transition from light as a spatial object to a temporal process, we add another dimension to define the revolution, which will surely enrich our understanding of the historical event.

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