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Semantic Flexibility in Scientific Practice: A Study of Newton's Optics

Michael Bishop

Most people, no matter how sophisticated their grasp of science or its history, believe that scientific language is special. It can be distinguished from the language of politics, art, and religion by its rigid precision. Exactly what this rigid precision amounts to is a matter of heated philosophical controversy. We can abstract away from the controversy by focusing on a doctrine that is common to almost all views of scientific language, semantic essentialism. According to semantic essentialism, any scientific term that appears in a well-confirmed scientific theory has a fixed kernel of meaning.[1] My aim in this paper is to overthrow the dogma of semantic essentialism, and by doing so, uncover some insights about the nature of scientific rhetoric and argumentation. These insights have been hidden by a blinkered adherence to a view that fails to recognize the suppleness and flexibility of scientific language.

The paper's main body has six sections. Section 1 shows how semantic essentialism has been used to interpret Newton's early writings on optics. Section 2 argues that the essentialist interpretations of Newton's first publication are uncharitable and unmotivated. A more context-sensitive reading of this work leads us to see that as Newton marshals more evidence for his view, his arguments tend to employ steadily bolder concepts. Section 3 sketches the central issues raised in two criticisms of Newton's first publication and in Newton's responses to them. We see how Newton understood the central concepts he employed in his first publication. Section 4 uncovers a heretofore unrecognized anomaly in Newton's optical writings: In June 1672, Newton posted, probably in one envelope, inconsistent accounts of the central concept he employed in his first publication. How could this be? Ascribing to Newton such a blatant inconsistency requires some explanation. I suggest that, unbeknownst to Newton and to legions of interpret-

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ers, some of the concepts expressed in Newton's first publication were partially indeterminate, and hence permit different, and even inconsistent, interpretations. Section 5 proposes two general considerations in favor of a semantically sensitive view of scientific language that are not contingent on the details of any particular historical episode. And, finally, section 6 briefly explores some philosophical implications of recognizing the flexibility of scientific language.

A word about semantics and terminology. I often say that a term expresses a concept and that concepts make certain presuppositions or assumptions. Such talk is very loose and informal. Let me state my assumptions more formally. A particular use of a term can express a concept, and that concept is the meaning of the term. A concept has a certain content, and that content can be represented by one or more descriptions, perhaps very complicated descriptions. For example, the term *bachelor* expresses a concept whose content can be represented by descriptions such as "an unmarried man." (That many will reject some or all of these assumptions is of no matter. The main points in this paper stand, though somewhat altered, if we adopt an alternative view of meaning.[2])

1. Traditional interpretations of Newton's early optical writings

Most seventeenth-century theories of the nature and behavior of light employ *light ray* as the central explanatory concept. When Newton published his first paper in 1672, the conventional view of light and colors held that white light consisted of rays that were basic and homogeneous. Different colors were the result of different modifications of white light. Red light was the result of a modification of white light, blue light was the result of a different modification of white light, and so on. Newton tried to turn the conventional view of colors on its head. He proposed that each particular color of light is homogeneous. Red light consists of rays that are all of a kind, as does blue light, and yellow light. White light is a mixture of light of all different colors; it consists of heterogeneous light rays.

What did Newton mean by the term *light ray*? This question, as posed, invites an essentialist answer (Wittgenstein 1953). To the best of my knowledge, every historian who has tackled the question has argued that *light ray* possessed some fixed kernel of meaning for some significant portion of Newton's career. For example, A. I. Sabra (1967) and Vasco Ronchi

(1970) argue that throughout his entire career, Newton employed a concept of light ray that presupposes that light is made of particles. Of course, the particle view of light was opposed by many of Newton's contemporaries, notably Hooke and Huygens. They believed that light consists of waves propagated through a pervasive ether.

The view that Newton always employed a particle concept of light ray has fallen out of favor. Alan Shapiro (1975) has argued (rightly in my view) that Newton's concept of light ray did not always presuppose a particle view of light. Shapiro retains, however, the semantic essentialism of the Sabra-Ronchi view. According to Shapiro, early in Newton's career, Newton's concept of light ray always presupposed that individual light rays are monochromatic. Jed Z. Buchwald (1989, 6–7) has recently embraced something like Shapiro's interpretation of Newton's optical concepts.

Shapiro's main argument springs from the following passage of Newton's *Optical Lectures*, which Newton gave prior to his first publication:

> If, however, someone has difficulty conceiving of several successive rays in the same straight line, let him imagine in place of the line OF a small space (in a physical sense equivalent to the line) in which many parallel but indefinitely close rays flow, so that they may be considered as sensibly coincident. With these premises, it is known from Lects. 4, 5, 6 that these rays must not at all be conceived of to be similar, but a mixture of red-, yellow-, green-, blue-, and purple-making rays together with all their intermediate gradations. (qtd. in Shapiro 1984, 145–47)

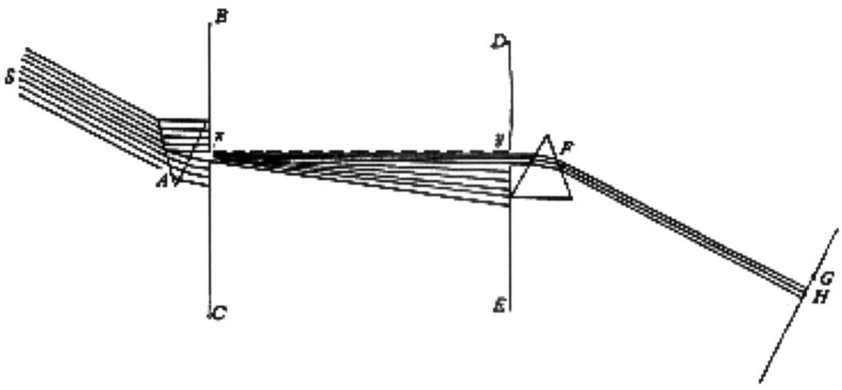

Fig. 1. Chromatic Dispersion. Reproduced with kind permission of Cambridge University Press. From Shapiro 1984, 144.

From this passage, Shapiro concludes that Newton's concept of light ray presupposes that light rays are monochromatic. Shapiro's line of argument runs as follows: When Newton defines or describes *light rays*, he typically says that light has "parts." The *Optical Lectures* makes it "clear, finally, what Newton *meant* by the 'parts' of light: the 'parts' are the rays of different color, whether they are constituted of atoms or rays as conceived in a wave theory of light" (Shapiro 1975, 207; emphasis added).

Shapiro is absolutely right that in the above passage, Newton takes it for granted that light rays are monochromatic. The rays represented in figure 1 by OF are "a mixture of red-, yellow-, green-, blue-, and purple-making rays together with all their intermediate gradations." But it is not clear that Newton is here offering an account of what he *meant* by *parts* of light. And even if we grant that what Newton means by *light ray* in this particular context is monochromatic rays, it does not follow that this was a dogmatic assumption always implicit in Newton's early work. Shapiro, however, argues that it was:

> Newton would continually attempt to placate his opponents by showing that his theory of colors does not depend on an emission theory of light, but there was one point on which he would not yield—white light is a heterogeneous mixture of all colors. . . . [Newton's] 'dogmatism' reemerges in the assumption that colors are present in white light before refraction. (Shapiro 1975, 208)

The problem with Shapiro's suggestion is that Newton's discussion about the nature of light rays in the *Optical Lectures* is not an attempt to specify what Newton always (or even often) meant by the expression *light ray* or by *parts* of light. It is the conclusion of a long argument. Newton signals this by prefacing his remarks about the monochromatic nature of light rays with the phrase "it is known from Lects. 4, 5, 6. . . ." In these lectures, Newton describes a number of experiments that were supposed to support his theory of color. So, in the above context, Newton takes for granted the assumption that light rays are monochromatic, but only after having argued for that assumption.

Semantic essentialism ascribes to Newton a static concept of light ray, a concept that for some significant portion of Newton's career always made some definite substantive assumption about optics. These essentialist views all rest on the same mistake—illicit generalization. Semantic essentialists are perfectly correct to point out that Newton sometimes uses concepts that presuppose central elements of his own theories. However, simply because a scientist uses a concept that makes certain strong assumptions in one context, it does not follow that the scientist uses that concept in all contexts. To make this point, let us turn to Newton's first publication and some of its aftermath.

2. Interpreting Newton's first publication

Isaac Newton submitted a paper to the Royal Society in February of 1672, at the request of the Society's Secretary, Henry Oldenburg. It was Newton's first publication, and in it he defends his theory of light and colors. By focusing on Newton's descriptions of two experiments, I will argue that the semantic essentialists are mistaken about what presuppositions are inevitably implicit in Newton's concept of light ray. My goals, however, are not primarily critical. I want to argue that by embracing a context-sensitive interpretation of scientific expressions, we get insights about scientists' argumentative and rhetorical strategies that semantic essentialism hides. By abandoning essentialism in favor of a more flexible view of scientific language, we will be open to seeing how Newton's concepts change as a text develops.

2.1. Newton's crucial experiment

Newton's discussion of the crucial experiment in his first publication begins by noting that, after a circular beam of white light passes through a prism, it fans out. What explains this prismatic dispersion (also known as *chromatic dispersion*, since the light exiting the prism fans out into a spectrum of colors)? To answer this question, Newton proposes his *crucial experiment*. It is designed to show that light disperses upon exiting the prism because white light consists of light rays of different degrees of "refrangibility"; in other words, white light consists of rays that are bent to different degrees by the prism. Newton explains, "I took two boards, and placed one of them close behind the Prisme at the window, so that the light might pass through a small hole." Newton then took another board with a small hole in it, placed it about twelve feet from the first board, and placed a prism behind the hole in this second board (see fig. 2):

> This done, I took the first Prisme in my hand, and turned it to and fro slowly about its *Axis*, so much as to make the several parts of the Image, cast on the second board, successively pass through the hole in it, that I might observe to what places on the wall the second Prisme would refract them. And I saw by the variation of those places, that the light, tending to that end of the Image, towards which the refraction of the first Prisme was made, did in the second Prisme suffer a Refraction considerably greater then the light tending to the other end. (Newton 1672a in Turnbull 1959, 94–95)

Newton explains the dispersion as follows: "And so the true cause of the length of that Image was detected to be no other than that *Light* con-

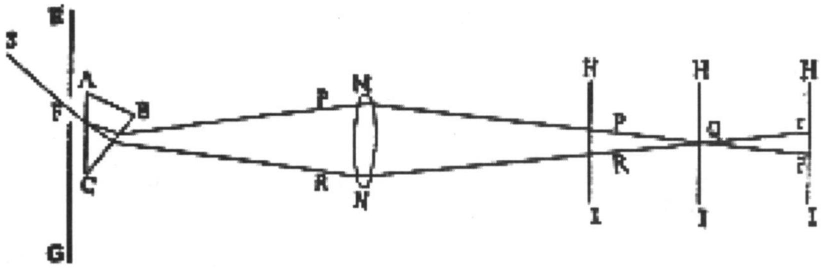

Fig. 2. Newton's Crucial Experiment. Reproduced with kind permission of Cambridge University Press. From Turnbull 1959, 166.

sists of *Rays differently refrangible*, which, without any respect to a difference in their incidence, were, according to their degrees of refrangibility, transmitted toward divers parts of the wall" (95). This was Newton's crucial experiment.

Although Newton opens his article by saying that he wants to address "the celebrated phenomena of colours," his discussion of the crucial experiment to this point is silent about the spectral colors produced by the prism. The phenomenon Newton focuses on is the fanning out of light upon exiting the prism. So, *pace* Shapiro and Buchwald, it is gratuitous to suggest that, in this particular context, Newton is employing a concept of light ray that presupposes anything about the nature of colors. Further, *pace* Sabra and Ronchi, there is no reason to suppose that, up to this point, Newton's discussion of the crucial experiment presupposes anything very specific about the substructure of light. A close examination of the crucial experiment shows at the very least that the semantic essentialists are wrong about what was inevitably implicit in Newton's concept of light ray. Of course, that is not to say that the discussion is altogether free of presuppositions. It assumes (perhaps among other things) that light rays usually travel in straight lines and that the light entering the prism consists of many light rays. Although the concept of light ray Newton employs in his discussion of his crucial experiment does not seem to be an especially interesting one, I shall argue that it is in fact an extraordinarily interesting concept. The explanation for this, however, will have to wait until section 5.

2.2. The prism-lens experiment

After a brief discussion of telescopes and microscopes, Newton sets down his theory of colors in thirteen "doctrines." In order to convince us that white light consists of light of all different colors, he describes his prism-lens experiment. Newton began by passing a circular beam of light through a prism.

> Then place a *Lens* of about three foot radius . . . at the distance of about four or five foot from thence, through which all those colours may at once be transmitted, and made by its Refraction to convene at a further distance of about ten or twelve foot. If at that distance you intercept this light with a sheet of white paper, you will see the colours converted into whiteness again by being mingled. But it is requisite, that the Prisme and Lens be placed steddy, and that the paper, on which the colours are cast, be moved to and fro; for, by such motion, you will not only find, at what distance the whiteness is most perfect, but also see, how the colours gradually convene, and vanish into whiteness, and afterwards having crossed one another in that place where they compound Whiteness, are again dissipated, and severed, and in an inverted order retain the same colours, which they had before they entered the composition. . . .
>
> In the annexed design of this Experiment, ABC representeth the Prism set endwise to sight, close by the hole F of the window EG. Its vertical Angle ACB may conveniently be about sixty degreés; MN designates the *Lens*. Its breadth 2 1/2 or 3 inches. SF one of the streight lines, in which difform Rays may be conceived to flow successively from the Sun. FP and FR two of those Rays unequally refracted, which the *Lens* makes to converge toward Q, and after decussation to diverge again. And HI the paper, at divers distances, on which the colors are projected: which in Q constitutes *Whiteness*, but are *Red* and *Yellow* in R, r . . . and *Blew* and *Purple* in P, p. . . . (Newton 1672a in Turnbull 1959, 101)

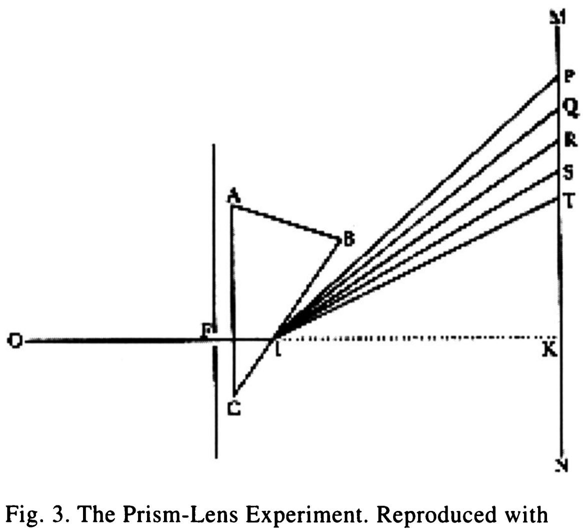

Fig. 3. The Prism-Lens Experiment. Reproduced with kind permission of Simon & Schuster, Inc. From Thayer 1953, 79.

This description of the prism-lens experiment seems to employ a bolder notion of light ray than did the crucial experiment. Newton explicitly assumes his own view of prismatic dispersion—white light consists of "difform Rays," rays that are differently refrangible. Does it follow that Newton always used such a concept? No. In a context where prismatic dispersion was the issue, such as in his discussion of the crucial experiment, Newton need not have used this particular concept. And as we have already seen, he did not. To use a concept that assumed his views about prismatic dispersion when arguing for his views about prismatic dispersion would have begged the question. But in *this* context, where Newton has already justified his theory of prismatic dispersion (at least to his own satisfaction) and is no longer arguing for it, he feels free to use the assumption that white light consists of rays that are differently refrangible.

Given the assumptions that light rays are rectilinear and are differently refrangible, Newton argues that the prism-lens experiment supports his seventh "doctrine"—that white light is a mixture of all different colors. We can sketch Newton's argument as follows: We can tell by observation that the rays between P and R (see fig. 3) produce many different colors. Since, according to the crucial experiment, each ray has its own degree of refrangibility, each is refracted independently by the lens. These rays then travel in straight lines to Q. We can tell by observation that at Q, the light appears white. In this particular experiment, a mixture of all the spectral colors produces white light. Therefore, white light is a mixture of all colors of the spectrum.

We may legitimately wonder whether this conclusion comes too fast. And we may legitimately wonder whether Newton employs "reasonable" assumptions (whatever that means). But the argument from the prism-lens experiment does not employ a concept that presupposes Newton's theory of color. Newton's argument does not assume precisely what it sets out to prove.

The context-sensitive reading of concepts allows us to ascribe to a scientist a series of *layered arguments*. For example, early in a work, Newton can employ a relatively weak concept of light ray to argue that light rays have interesting properties *A*, *B*, and *C*. After doing this, he can employ stronger concepts—concepts that make some of the assumptions he has already defended (like *A*, *B*, or *C*)—to argue that light rays have even more and different interesting properties. We see that Newton proposed layered arguments in his first publication. Early on, in his discussion of the crucial experiment, Newton's concept presupposes very little about the nature of light. But later, in his discussion of the prism-lens experiment, Newton's concept presupposes more—that white light consists of rays of different refrangibility. If we insist that Newton was "consistent" in his use of the expression *light ray*, we must concede that he could never have employed this kind of argumentative strategy.

3. Newton on light rays: Responses to objections

In his first publication, Newton presents a series of arguments that employ somewhat different concepts. Early on, the light ray concept explicitly makes fairly uncontentious assumptions. But later, after having defended more contentious hypotheses, Newton could employ concepts that assumed those stronger hypotheses. But how did Newton interpret his own concept of light ray? To answer this question, let us turn to Newton's responses to a pair of objections raised against his first publication.

3.1. Newton and Hooke

In his paper, Newton states that "it can be no longer disputed . . . perhaps whether Light be a Body" (1672a, 100). Many critics, including Robert Hooke, understandably read this as an endorsement of an emission theory of light, in which light consists of particles projected from a luminous body. Hooke's rebuttal of Newton's paper does not question its experimental findings. In fact, Hooke begins by agreeing with Newton's experimental findings since he had already made "many hundreds" of those trials and "found them soe." Hooke argues that his mechanical hypotheses could explain Newton's findings "without any manner of difficulty or straining" (Hooke 1672, 111). In fact, Hooke affirms, "I can assure Mr Newton I cannot only salve all the Phaenomena of Light and colours by the Hypothesis, I have formerly printed and now explicate yt by, but by two or three other, very differing from it" (113). Hooke believed that many theories of light could explain Newton's observational findings.

Newton responds to Hooke by arguing that (1) his explanation of dispersion is independent of any hypotheses about the substructure of light and (2) Newton's theory of dispersion is superior to Hooke's, which Newton deemed "not onely *insufficient*, but in some respects *unintelligible*" (Newton 1672c, 176). The first line of defense is our only concern here. Newton begins by denying that the statement in his original paper, "it can be no longer disputed . . . perhaps whether Light be a Body" (1672a, 100), implied an emission theory of light:

> 'Tis true that from my Theory I argue the corporeity of light, but I doe it without any absolute positivenesse . . . & make it at most but a very plausible consequence of the Doctrine, & not a fundamentall supposition. . . . But I knew that the Properties wch I declared of light were in some measure capable of being explicated not onely by that, but by many other Mechanicall Hypotheses. And therefore I chose to decline them all, & speake of light in generall termes, considering abstractedly as something or other propagated every way in streight lines from luminous bodies, without determining what that thing is, whether a confused mixture of difform qualities, or modes of bodies, or of bodies themselves, or of any virtues powers or beings whatsoever. (Newton 1672c, 173–74)

Here Newton insists that his original paper did not assume anything about the underlying structure of light. Light rays are the "something or other propagated every way in streight lines from luminous bodies." In this particular context, Newton intends to express, and does express, a concept that assumes that a light ray is a visible beam of light; that concept does not assume anything about the underlying make up of light rays. Newton read that agnosticism back into his original paper. Why did Newton insist on this interpretation? Very simply, it was the only concept that would serve his rhetorical and argumentative purposes. Newton was responding to Hooke's allegation that his findings failed to support *any* of his conclusions—either about the substructure of light or about the proper explanation of prismatic dispersion. Newton wanted to avoid the first issue and trounce Hooke on the second, so he denied that he needed any assumption about the substructure of light. But he did need *some* notion of light ray in order to defend the proposition that white light consists of *rays* of different degrees of refrangibility. So, given this pair of constraints, he was forced to embrace a concept of light ray that makes no assumptions about the substructure of light: Light rays are the "something or other propagated every way in streight lines from luminous bodies." So far, so good.

3.2. Newton and Pardies

Pardies's response (actually, his second response) to Newton's paper proposes a specific competing explanation for chromatic dispersion—the diffusion hypotheses defended by Hooke and Grimaldi. Ironically, the account of chromatic dispersion defended by Hooke (among others) was an essential part of Pardies's response to Newton, but not of Hooke's. Hooke's main point is quite general: Newton's findings were insufficient to force a choice between competing theories about the underlying nature of light and colors. Pardies's point is much more specific. He argues that Newton's findings do not compel a choice between two specific competing mechanical explanations of chromatic dispersion. To understand Newton's response, we must turn briefly to the diffusion hypothesis Pardies was championing.

The explanation of chromatic dispersion Hooke offered in his *Micrographia* (1665) employs both a conventional modification view of colors and a continuum theory of light. Continuum theories of light hold that light is the propagation of a state (a pressure or motion) through some intervening medium (an ether). Hooke explained that between a luminous body and the eye is a "pellucid body" in which "the appulse of the luminous body may be communicated or propagated through it to the greatest imaginable distance in the least imaginable time" (56). He adds, "The motion is propagated every way through an *Homogeneous medium* by *direct* or *straight* lines extended every way like Rays from the center of a Sphere" (57). Notice that, although Hooke defends a continuum (or wave) theory of light, *light ray* is the central explanatory term. This is an important point of contact between Hooke and Newton. It allows for the possibility (but does not guarantee) that they will sometimes express the same concepts of light ray in their explanations.

Hooke explains colors as a kind of modification of white light. He supposes "ACFD to be a physical ray, or ABC and DEF to be two mathematical rays, trajected from a very remote point of a luminous body through an homogeneous transparent medium LLL" (see fig. 4). Pulses of light (DA,

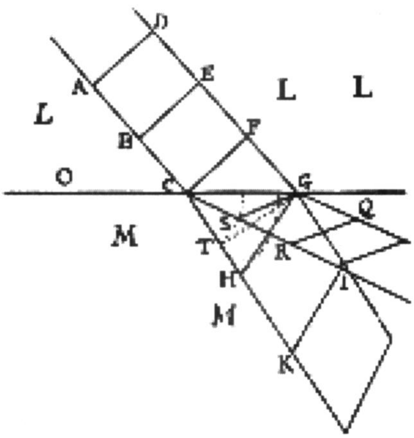

Fig. 4. Hooke's Modification View of Colors. Reproduced with kind permission of Science Heritage Limited. From Hooke 1665/1987, schem. VI, fig. 1.

EB, FC) are "small portions of the orbicular impulses which must therefore cut the rays at right angles" (57). Notice that, in figure 4, the pulses of light (AD, BE, CF) are perpendicular to the parallel light rays (AC and DF). While the ray that enters medium MMM (AC) travels from C to H, the other ray travels only from F to G. This causes the post-refraction pulses (GH and IK) to be oblique to the rays. According to Hooke, whenever the pulse is oblique to the rays, colors are produced (blue along ray CK and red along ray GI). So colors are produced when white light is modified in the appropriate way.

Hooke's explanation of chromatic dispersion involves two factors. The first is diffusion. When physical ray ACFD (see fig. 4) first hits the new medium (MMM), the part of the pulse that hits the new medium first (ACK) is more "impeded by the resistance of the transparent medium, than the other part" of the pulse. The later part of the pulse (DGI) "will be promoted, or made stronger, having its passage already prepared" for it by the earlier part of the pulse. So the later, red edge of the pulse will spread into the adjacent medium more than it would have if its path had not been "already prepared." So in figure 5, without diffusion, the ray EBAF would refract along BONA. But since the red edge diffuses into the adjacent medium, EBAF actually refracts along BOMA (63).

The second factor involved in dispersion is the fact that the physical rays coming from the sun are not parallel. So both physical rays EBAF and

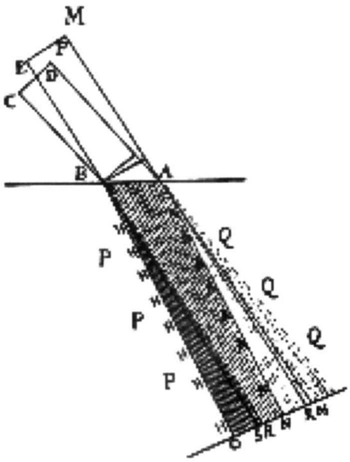

Fig. 5. The Diffusion Hypothesis. Reproduced with kind permission of Science Heritage Limited. From Hooke 1665/1987, schem. VI, fig. 4.

CBAD (which might be coming from different edges of the sun) are refracted. Ray CBAD is refracted along the ray with edges BO and Q (for a fuller discussion of Hooke's theory, see Shapiro 1975).

In his response to Pardies, Newton explicitly makes reference to phenomena at the unobservable, mechanical level when defining his notion of light ray:

> [B]y the *rays* of light I understand its least or indefinitely small parts which are independent of one another; such as are all those rays which luminous bodies emit either simultaneously or successively along straight lines. For both the collateral and the successive parts of light are independent; since some of the parts may be intercepted without the others and be separately reflected or refracted into any areas. (1672b, 164; trans. in Shapiro 1975, 200)

Newton tells Pardies to understand *light rays,* as used in the original paper, as having "least or indefinitely small parts." And these parts "are independent of one another." Newton reads these assumptions back into his original paper.

Why did Newton embrace these assumptions about the underlying structure of light rays here? Consider the context. Pardies had advanced a diffusion theory to explain chromatic dispersion: the leading edge of a pulse is more "impeded by the resistance" of the medium than the later edge, and so this later part spreads out (see figure 5). This is a mechanical explanation of chromatic dispersion. On the one hand, it would have been very awkward to attempt to describe, much less attempt to refute, a *mechanical explanation* of dispersion without being able to talk about the phenomena at the *mechanical* level; it would be like trying to explain why a car will not run without talking about any of its parts. On the other hand, Newton did not want (or need) to embrace a full-blown emission or continuum theory of light. In fact, in the line previous to the above quotation, Newton said that "the doctrine explaining light and colours is based solely upon the properties of light, apart from explanatory hypotheses" (1672b, 169). Given these constraints, Newton could insist that he did not need to assume any full-blown "explanatory hypotheses" while claiming that light rays are the "least or indefinitely small parts" that "are independent of one another."[3]

4. Inconsistency and partially indeterminate concepts

A brief consideration of the responses to Hooke and Pardies uncovers a heretofore unrecognized anomaly in Newton's optical writings. In June 1672, Newton posted, probably in one envelope, inconsistent accounts of what he assumed about the nature of light rays in his first publication. In answering Hooke, Newton claimed that his first publication completely eschewed the unobservable level of mechanical hypotheses. The response to Pardies, however, explicitly does not relinquish reference to the unobservable, mechanical level. I will try to explain and defend this surprising allegation.

In his response to Hooke, Newton defined a visible beam of light (call this an H-ray); in his response to Pardies, he defined the least or indefinitely small independent parts of light (call this a P-ray). Visible beams cannot be indefinitely small, since they must be visible. So H-rays are not identical to P-rays. One can describe Newton's experiments in terms of H-rays or P-rays without inconsistency. Had Newton simply been explaining the phenomena from different perspectives, there would be no worries about inconsistency. The problem arises because Newton is giving different accounts of what he was saying in his original paper. *Newton's answers were interpretations of the exact same text!* In his original paper, Newton argued that light fans out after passing through a prism because white light consists of *rays* of different degrees of "refrangibility." What exactly did Newton mean by *rays*? In his response to Hooke, he said *light beams*, and in his response to Pardies he said *the least or indefinitely small parts of light*. Given the assumption that *light ray* meant something determinate in his first publication, both answers cannot be correct. They are inconsistent.

On closer examination, we can see that Newton's answer to Hooke is explicitly about *light*; he does not mention light rays. Newton's answer to Pardies is about light *rays*. Can this save Newton from inconsistency? No. Newton certainly knew that his response to Hooke describes his experiments in observational terms while his response to Pardies does not. Since he was responding to these objections at about the same time, it isn't surprising that he drew a terminological distinction between (observable) light and (unobservable) light rays. As I've already argued, there is no inconsistency in describing the phenomena in terms of light and in terms of light rays. But I am not arguing that Newton's explanations *of the phenomena* are inconsistent. Rather, my claim is that Newton's two accounts of what he was saying in his original paper are inconsistent. The question that brings on the trouble is the following: In his original paper, what exactly did Newton mean by *rays*? In his response to Hooke, he said he meant *light*, but, in his response to Pardies, he said he meant *light ray*. These are not the same as Newton defines them. The terminological distinction between *light* and *light ray* cloaks this inconsistency, but does not explain it.

Semantic essentialists will refuse to believe that Newton could have "flip-flopped" so blatantly, by using incompatible concepts as they suited his purposes. But this reaction is unwarranted. It fails to recognize that scientific concepts are not pristine, unchanging inhabitants of Plato's Heaven. They do real work. And real work gets done in real contexts. Newton was facing very different challenges in the responses from Hooke and Pardies. To overcome these challenges, Newton required different resources. Against Hooke's very broad attack on Newton's explanation of prismatic dispersion, Newton was best served to talk about his experiments in observational terms. Against Pardies's claim that a specific competing mechanical hypothesis could explain the data perfectly well, Newton was forced to go beyond the observational level in talking about his experiments. There is no suggestion here that Newton was defending inconsistent *theories* of light in his responses to Hooke and Pardies. Newton defended a single theory of light, but he was able to express a number of different concepts and refer to a number of different features of light when he used the explanatory expression *light ray*. He could talk about light rays as observable lines of light, as the least or indefinitely small independent parts of light, as traveling particles of light, and in a number of other ways as well.[4]

There is another, better way to avoid saddling Newton with inconsistency. Suppose the concept of light ray Newton used in his first publication is in some (though not all) respects *indeterminate*. The use of a term T expresses an *indeterminate* concept just in case there is no fact of the matter about whether any one of a certain class of descriptions correctly represents the content of that concept. So suppose the concept of light ray that Newton employed in his first publication is indeterminate with respect to the nature of the substructure of light. There was no fact of the matter about whether *light ray* expressed a concept that assumed anything about the substructure of light. To put the point crudely, the concept of light ray is a partly empty vessel that can be "filled in" later in different ways in different contexts. If this is correct, then Newton is not guilty of inconsistency if he "fills in" the concept differently in different contexts. (Nor are other interpreters, for that matter.) Since Newton had different rhetorical and argumentative aims when responding to Hooke and Pardies, he chose to interpret his original expressions in somewhat different ways.[5] If this reading is correct, then Newton may have made a mistake about the nature of his original concept. Like centuries' worth of interpreters, Newton may have failed to recognize the concept's indeterminate nature. Unless we suppose that speakers have privileged access to the meanings of their words, however, this mistake is neither surprising nor particularly significant.

Scientific expressions (like many others) are often supple and open-ended. The possibility of expressing a partially indeterminate concept is an important (and neglected) element of scientific practice. I suspect that indeterminate concepts are fairly common in descriptions of experiments that are meant to convince people with divergent theoretical commitments. Indeterminate concepts allow scientists considerable flexibility to respond in the future to very different kinds of criticisms that might come from very different quarters. So my point here is not to vex Newton with charges of conceptual confusion, carelessness, or inconsistency. The possibility of expressing partially indeterminate concepts allows Newton to propose supple arguments that can be wielded in different ways under different circumstances. Without this conceptual flexibility, Newton's argumentative and rhetorical practices would have been much different, and much poorer, than they actually were.

5. General considerations in favor of semantic flexibility

It is dangerous to draw general conclusions about the nature of science from a single case study. Thus, I want to propose two general considerations that drive us to conclude that semantic flexibility is a pervasive feature of scientific practice.

5.1. The nature of scientific argument

One might suppose that it is terribly uncharitable to suggest that Newton's use of the term *light ray* expressed different, and sometimes inconsistent, concepts. Isn't it more generous to suppose, along with semantic essentialists, that at various stages in his career, Newton used a single concept of light ray? No. Ascribing to Newton a rigid concept of light ray is misguided charity. While it does grant him a stubborn sort of narrow consistency, it prevents us from interpreting him as proposing a series of layered arguments—arguments that employ steadily bolder concepts as more substantive hypotheses are defended—or supple arguments that can be wielded in different ways under different circumstances.[6] Further, and perhaps more troubling, semantic essentialism requires that we interpret Newton as having proposed at least some circular, question-begging arguments. If we adopt the view that Newton *always* expressed a concept that assumed X (his theory of colors, the emission theory, or whatever), then any argument he could have given for thinking that light rays are X would have been question-begging. And the semantic essentialist could know this without even looking at the text! (If this be charity. . . .)

This is a perfectly general point. Suppose that for some scientific term T, we assume that it expresses a concept that always makes the substantive assumption that Ts are X. Whenever a scientist argues that Ts are X, we are forced to interpret that argument to be question-begging. For example, suppose we claim that the gene concept *always* involves the assumption that genes are on chromosomes. That genes are on chromosomes is, of course, a substantive assumption for which scientists can argue and give evidence. Now suppose that a scientist sets forth such an argument and uses the expression *gene* in the premises. Her argument will be circular—it will presuppose exactly what it sets out to prove. It is certainly possible for scientists to present circular arguments, and there are undoubtedly cases in which scientists have done so. However, adopting a rigid view of scientific concepts guarantees that scientists will be incapable of arguing noncircularly for their most basic assumptions. Surely, it is a mistake—on hermeneutic and historiographical grounds—to begin a study of an episode with a guarantee that scientists will inevitably propose question-begging arguments. Yet this is precisely what semantic essentialists do.

5.2. Consistency with psychological findings

One of the most robust findings in psychology over the past few decades is that concepts are not represented in terms of singly necessary and jointly sufficient conditions (see Smith and Medin [1981] for a summary). While psychologists have proposed various models of how concepts are represented, the negative point is not news to philosophers. It was one of Wittgenstein's most celebrated and widely accepted insights:

> Consider for example the proceedings that we call 'games.'. . . What is common to them all?—Don't say: "There *must* be something common, or they would not be called 'games'"—but *look and see* whether there is anything common to all. . . .
>
> And the result of this examination is: we see a complicated network of similarities overlapping and criss-crossing: sometimes overall similarities, sometimes similarities of detail. (1953, 66)

Suppose some concept is represented in terms of a set of non-necessary conditions. It follows that, for each of those non-necessary conditions, the concept applies in some cases where it does not. One goal of this paper is to apply this insight, deftly articulated by Wittgenstein and repeatedly confirmed by psychologists, to scientific practice. If Newton's concept of light ray is represented by conditions, some of which are non-necessary, then there will be cases in which Newton properly applies the term *light ray* even though one (or more) of its defining conditions do not obtain. As a result, we should expect Newton to apply his concept of light rays to entities with somewhat different features—observable lines of light, the least or indefinitely small independent parts of light, or traveling particles of light.

One might argue that scientific concepts are special and different from our everyday, run-of-the-mill concepts; one might insist that they are represented in terms of only necessary conditions. This is, of course, perfectly possible. But, given the available evidence, the burden of proof must be on the one who makes this suggestion. Until such a case is made, if we want a broad naturalistic framework that accounts for scientific change, it seems reasonable to adopt a philosophically and psychologically plausible story about the nature of scientific concepts. Such a story requires that we reject semantic essentialism.

6. Implications of semantic flexibility

Once we recognize the possibility that scientific terms are semantically flexible, both in terms of the concepts they express and in terms of what they refer to, we are forced to transform our views of a number of philosophical issues. I will focus briefly on two such issues, reductionism and theory-change.

6.1. Reductionism

Semantic flexibility has important implications about the reductionism issue. Philosophers often wonder whether the insights, laws, or explanations of theory T1 can be or have been reduced to those of theory T2. For example, currently there is disagreement about whether classical genetics has been reduced to molecular genetics (see Kitcher 1984 and Waters 1990). Traditionally, there are two elements to theory reduction. First, there must be some sort of connection between the explanatory terms of the theories. Typically, the expressions of the reduced theory will be defined (extensionally) in terms of the expressions of the reducing theory. For example, in the case of genetic reductionism, the central issue philosophers have debated is whether the *gene* of classical Mendelian genetics has been (or can be) reduced to molecular biology. The second element of theory-reduction is that the laws of the reduced theory must be derivable from the laws of the reducing theory (together with "bridge principles," such as the above-mentioned definitions, that connect the vocabularies of the theories). In the case of genetic reductionism, this would involve showing how, starting from molecular genetics and bridge principles, it is possible to derive the laws of Mendelian genetics (e.g., the law of independent assortment).

Now suppose that the terms of scientific theories are semantically flexible: On different occasions, they can express different concepts and they pick out different (or sometimes nonexistent) features of the world. What happens to reductionism? The issue fragments. There are no longer just two competing positions with respect to some allegedly reduced entity—reductionism or antireductionism. The issue becomes: *Which* senses of a term of one theory are reducible to *which* senses of terms of another theory? Many different positions on this question are available. And there is no *a priori* reason to believe that the most extreme positions are the most plausible candidates. So consider again genetic reductionism. It *may* be that *gene* as used by the most sophisticated spokespersons of classical genetics was always used univocally. And it may be that contemporary genetic terms are always used univocally. If so, it *may* be that one of the extreme positions, reductionism or antireductionism, is true. What is peculiar about the debate on genetic reductionism is that the substantial middle ground has been completely overlooked. It may well be that some ways in which classical geneticists used the term *gene* do reduce to molecular genetics while other senses of the term do not.

6.2. Theory-change

The context-sensitive approach has potentially far-reaching implications for general views about the nature of theory-change in science. The most common positions tend to rely implicitly on the assumption that a scientific theory has a single semantic structure, in which each term expresses only a single concept or refers to only a single object or type of object.[7] For example, some nonrealists argue that different theories are conceptually (or semantically) incommensurable. But what does it mean to say that Newton's concept of light ray is incommensurable with anything when he (and his opponents) had so many concepts at their disposal? In contrast, most realists argue that a term employed by two different but successful theories refers to the same thing (or same type of thing). But Newton's expression *light ray* could refer to many different things—a visible beam, an irreducibly smallest section of propagating light, a traveling particle of light, or an indefinitely small section of propagating light. If Newton by himself could refer to many different kinds of things with the term *light ray*, how could the expression, when used by Newton and his opponents, possibly refer to the same kind of thing on every occasion of use? The context-sensitive approach to scientific terms defended in this paper suggests that some of the most dominant models of scientific change are too crude to account for the richness and subtleties present in actual episodes of scientific debate and theory-change.

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Notes

1. Many currently dominant views about the nature of scientific theory-change suppose that scientific terms have a fairly static semantic structure. Some nonrealists, such as Kuhn (1962/70) and Feyerabend (1975/88), argue that the central explanatory terms of competing scientific theories are "incommensurable"—there is no theory-neutral language into which they can be translated without residue or loss. This view assumes that every time a scientific term is used, it expresses a concept that makes specific, substantive assumptions that render the term incommensurable with competing theories. In contrast, some scientific realists, such as Boyd (1984) and Putnam (1978), assume that a scientific term refers to a particular scientific kind every time it is properly used. This assumption allows the realist to argue that scientific language is often grounded in a corresponding reality. In both cases, scientific terms always have a fixed kernel of meaning.

2. The semantic view I adopt in this paper is not the currently dominant view among analytic philosophers. I adopt it because it seems to be the one that is presupposed by those who actually interpret scientific texts and, in particular, by those semantic essentialists who interpret Newton's early optical writings. The dominant view among analytic philosophers about semantics is that the meaning of a scientific kind term is simply its reference, the class of entities to which it refers. The main points of this paper can be easily transformed so as to take seriously this view of scientific language. Semantic essentialism is the view that a scientific term, when properly used, always refers to a single class of entities. A close textual analysis of Newton's early optical writings show that his central explanatory expression, *light ray*, refers to quite different classes of entities on different occasions. (For a defense of a context-sensitive theory of reference that has this kind of consequence, see Kitcher 1993.) On at least some occasions, there was no fact of the matter about what exactly Newton's expression referred to. (For a defense of this possibility, see Field 1973.)

3. The Pardies response presents a serious problem of interpretation. After claiming that he does not require any explanatory hypotheses, Newton presents a definition that seems to presuppose an emission theory of light. By asserting that the parts of light can "be separately reflected or refracted into any areas," Newton seems committed to the view that the parts of

light are projected through space. And this is possible only if we assume an emission theory is true and a continuum theory is false. How are we to resolve the apparent contradiction?

It is very important to see that this problem of interpretation arises for everyone. It is not unique to the account of Newton's concepts offered in this paper. For example, Shapiro suggests that Newton intended to give Pardies "a phenomenological definition, which asserts the observed property of light that every 'part' of a beam is reflected and refracted independently of any other 'part'" (1975, 201). While this resolution has a number of virtues, there is also an obvious problem. It leaves mysterious why Newton explicitly refers to the "least or indefinitely small parts" of light in his response to Pardies. That is not a "phenomenological definition" of *light ray*. Why didn't Newton simply define *light rays* phenomenologically, as the "something or other propagated every way in streight lines from luminous bodies"?

One way to resolve the apparent contradiction in Newton's response to Pardies is to recognize that Newton has many concepts of light ray available to him. Some of these presuppose an emission theory of light and some do not. He uses more than one of them in his response to Pardies. How could this have happened? I would suggest that in the response to Pardies, Newton is struggling, and failing, to articulate a mechanical concept of light ray that is neutral between his emission theory and rival continuum theories of light. Evidence for this struggle appears in an unpublished reprint of his first paper. Here, Newton appears to give an account of light ray that adverts to the mechanical level but does not presuppose either emission or continuum theories of light. Newton states that whether light rays are particulate or wave-like, "light is equally a body or the action of a body in both cases. If you call its rays the bodies trajected in the former [emission theory] case, then in the latter [continuum theory] case they are the bodies which propagate motion from one to another in right lines till the last strike the sense. The only difference is, that in one case a ray is but one body, in the other many" (Cohen 1958, 365).

4. Newton was perfectly capable of expressing a concept of light ray that presupposed an emission theory of light. Consider, for example, *Query 29* of the *Opticks*, in which Newton offered a particulate explanation of the refraction and reflection of light:

> Pellucid Substances act upon the Rays of Light at a distance in refracting, reflecting, and inflecting them, and the Rays mutually agitate the Parts of those Substances at a distance for heating them; and this Action and Re-action at a distance very much resembles an attractive Force between Bodies. If Refraction be perform'd by Attraction of the Rays, the Sines of Incidence must be to the Sines of Refraction in a given Proportion, as we shew'd in our *Principles of Philosophy*: And this Rule is true by Experience. The Rays of Light, in going out of Glass into a *Vacuum*, are bent toward the Glass, and if they fall too obliquely on the *Vacuum* they are bent backward into the Glass and totally reflected; and this Reflexion cannot be ascribed to the Resistance of an absolute *Vacuum*, but must be caused by the Power of the Glass attracting the Rays at their going out of it into the *Vacuum* and bringing them back. (1730, 370–71)

In this passage, Newton brings the framework of the *Principia* to bear in explaining the refraction and reflection of light—a framework in which discrete bodies with mass are subject to forces. Newton explains refraction from glass to a vacuum as follows: A particle of light that enters the glass-vacuum border at an oblique angle is attracted toward the glass; thus its path is bent away from the normal (and its velocity decreases). The particulate concept of light ray, along with many others, was also available to Newton early in his career. As Shapiro (1984, 129–33) has noted, Newton employed a particulate concept of light ray in a passage in the *Optical Lectures*.

5. A *partially indeterminate* concept of light ray is not the same as a particular concept that is *agnostic* about the substructure of light, a concept we might explicate as "light rays whatever they are." If a token of *light ray* expresses an agnostic concept, it would be a

mistake later to interpret it in any other way. In particular, it would be a mistake to interpret it as a particle concept in one context and a wave concept in another. The agnostic concept has a perfectly determinate content that cannot be "filled in" later. The partially indeterminate concept, however, can later be properly interpreted as being a particle concept, and, in a different context, it can later be properly interpreted as not being a particle concept.

6. Laymon (1978) focused on the ways in which Newton idealizes his descriptions of the crucial experiment in responding to Lucas. Newton's response to Lucas is likely to provide further support for the context-sensitive view of Newton's concepts since it will probably exhibit more ways in which Newton was willing to employ the expression *light ray*.

7. Consider this objection: "We need to distinguish between the concept of light ray (or the reference of the term *light ray*) as used in Newton's optical *theory* and the variegated ways Newton might have used the expression in different situations. The former, proper use (unlike the latter, messy use) of the term expresses just one concept (or refers to one thing or one type of thing)." Something like this may well be behind the uncritical belief in semantic essentialism. But the objection presupposes an untenable view of scientific theories. A scientific theory is not simply a set of sentences that have a rigid, single fixed meaning. A scientific theory is better understood as a set of complex (individual and social) practices and problem-solving procedures. Kuhn (1962/70) is the *locus classicus* of this view of theories. See Kitcher (1993) for a sophisticated current treatment of this issue.

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