Part VII

MILL, WHEWELL, AND THE WAVE-PARTICLE DEBATE

Waves and Scientific Method

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1. Introduction

In 1802 a youthful Thomas Young, British physician and scientist, had the audacity to resuscitate the wave theory of light (Young 1802). For this he was excoriated by Henry Brougham (1803) in the *Edinburgh Review*. Brougham, a defender of the Newtonian particle theory, asserted that Young's paper was "destitute of every species of merit" because it was not based on inductions from observations but involved simply the formulation of hypotheses to explain various optical phenomena. And, Brougham continued:

> A discovery in mathematics, or a successful induction of facts, when once completed, cannot be too soon given to the world. But...an hypothesis is a work of fancy, useless in science, and fit only for the amusement of a vacant hour. (1803, p. 451)

This dramatic confrontation between Young and Brougham, it has been claimed, is but one example of a general methodological gulf between 19th century wave theorists and 18th and 19th century particle theorists. The wave theorists, it has been urged by Larry Laudan (1981) and Geoffrey Cantor (1975), employed a method of hypothesis in defending their theory. This method was firmly rejected by particle theorists, who insisted, with Brougham, that the only way to proceed in physics is to make inductions from observations and experiments.

In a recent work (Achinstein 1991), I argue, contra Laudan and Cantor, that 19th century wave theorists, both in their practice and in their philosophical reflections on that practice, employed a method that is different from the method of hypothesis in important respects; moreover, there are strong similarities between the method the wave theorists practiced and preached and that of 19th century particle theorists such as Brougham and David Brewster. In the present paper I will focus just on the wave theorists. My aims are these: to review my claims about how in fact wave theorists typically argued for their theory; to see whether, or to what extent, this form of reasoning corresponds to the method of hypothesis or to inductivism in sophisticated versions of these doctrines offered by William Whewell and John Stuart Mill; and finally to deal with a problem of anomalies which I did not develop in *Particles and Waves* and might be said to pose a difficulty for my account.

PSA 1992, Volume 2, pp. 193-204

2. The Method of Hypothesis and Inductivism

According to a simple version of the method of hypothesis, if the observed phenomena are explained by, or derived from, an hypothesis, then one may infer the truth or probability of that hypothesis. Laudan maintains that by the 1830s an important shift occurred in the use of this method. An hypothesis was inferable not simply if it explained known phenomena that prompted it in the first place, but only if it also explained and/or predicted phenomena of a kind different from those it was invented to explain. This version received its most sophisticated formulation in the works of William Whewell, a defender of the wave theory. In what follows I will employ Whewell's version of the method of hypothesis as a foil for my discussion of the wave theorist's argument.

Whewell (1967, pp. 60-74) offered four conditions which, if satisfied, will make an hypothesis inferable with virtual certainty. First, it should explain all the phenomena which initially prompted it. Second, it should predict new phenomena. Third, it should explain and/or predict phenomena of a "kind different from those which were contemplated in the formation of...[the] hypothesis" (p. 65). If this third condition is satisfied Whewell says that there is a "consilience of inductions." Whewell's fourth condition derives from the idea that hypotheses are part of a theoretical system the components of which are not framed all at once, but are developed over time. The condition is that as the theoretical system evolves it becomes simpler and more coherent.

Since both Laudan and Cantor claim that the wave theorists followed the method of hypothesis while the particle theorists rejected this method in favor of inductivism, it will be useful to contrast Whewell's version of the former with Mill's account of the latter. This contrast should be of special interest for two reasons. Both Whewell and Mill discuss the wave theory, which Whewell supports and Mill rejects; and each criticizes the other's methodology.

One of the best places to note the contrast in Mill is in his discussion of the "deductive method" (which he distinguishes from the "hypothetical method" or method of hypothesis) (Mill 1959, pp. 299-305). Mill asserts that the deductive method is to be used in situations where causes subject to various laws operate, in other words, in solving typical problems in physics as well as other sciences. It consists of three steps. First, there is a direct induction from observed phenomena to the various causes and laws governing them. Mill defines induction as "the process by which we conclude that what is true of certain individuals of a class is true of the whole class, or that what is true at certain times will be true in similar circumstances at all times" (p. 188). This concept of inductive generalization is used together with his four famous canons of causal inquiry to infer the causes operating and the laws that govern them. The second part of the deductive method Mill calls "ratiocination." It is a process of calculation, deduction, or explanation: from the causes and laws we calculate what effects will follow. Third, and finally, there is "verification": "the conclusions [derived by ratiocination] must be found, on careful comparison, to accord with the result of direct observation wherever it can be had" (p. 303).

Now, in rejecting the method of hypothesis, Mill writes:

> The Hypothetical Method suppresses the first of the three steps, the induction to ascertain the law, and contents itself with the other two operations, ratiocination and verification, the law which is reasoned from being assumed instead of proved (p. 323).

Mill's major objection to the method of hypothesis is that various conflicting hypotheses are possible from which the phenomena can be derived and verified. In his discussion of the wave theory of light, Mill rejects the hypothesis of the luminiferous ether on these grounds. He writes:

> This supposition cannot be looked upon as more than a conjecture; the existence of the ether still rests on the possibility of deducing from its assumed laws a considerable number of actual phenomena....most thinkers of any degree of sobriety allow, that an hypothesis of this kind is not to be received as probably true because it accounts for all the known phenomena, since this is a condition sometimes fulfilled tolerably well by two conflicting hypotheses; while there are probably many others which are equally possible, but which, for want of anything analogous in our experience, our minds are unfitted to conceive (p. 328).

With Whewell's ideas about prediction and consilience in mind, Mill continues:

> But it seems to be thought that an hypothesis of the sort in question is entitled to a more favourable reception if, besides accounting for all the facts previously known it has led to the anticipation and prediction of others which experience afterwards verified.... Such predictions and their fulfillment are, indeed, well calculated to impress the uninformed, whose faith in science rests solely on similar coincidences between its prophecies and what comes to pass.... Though twenty such coincidences should occur they would not prove the reality of the undulatory ether.... (pp. 328-9)

Although in these passages Mill does not discuss Whewell's ideas about coherence and the evolution of theories, it is clear that Mill would not regard Whewell's four conditions as sufficient to infer an hypothesis with virtual certainty or even high probability. The reason is that Whewell's conditions omit the first crucial step of the deductive method, the induction to the causes and laws.

If Laudan and Cantor are correct in saying that 19th century wave theorists followed the method of hypothesis and rejected inductivism, then, as these opposing methodologies are formulated by Whewell and Mill, this would mean the following: 19th century wave theorists argued for the virtual certainty or high probability of their theory by first assuming, without argument, various hypotheses of the wave theory; then showing how these will not only explain the known optical phenomena but will explain and/or predict ones of a kind different from those prompting the wave hypotheses in the first place; and finally arguing that as the theory has evolved it has become simpler and more coherent. Is this an adequate picture? Or, in addition, did wave theorists employ a crucial inductive step to their hypotheses at the outset? Or do neither of these methodologies adequately reflect the wave theorists' argument?

3. The Wave Theorists' Argument

Nineteenth century wave theorists frequently employed the following strategy in defense of their theory.

1. Start with the assumption that light consists either in a wave motion transmitted through a rare, elastic medium pervading the universe, or in a stream of particles emanating from luminous bodies. Thomas Young (1845) in his 1807 Lectures, Fresnel (1816) in his prize essay on diffraction, John Herschel (1845) in an 1827 review article of 246 pages, and Humphrey Lloyd (1834) in a 119 page review article,[1] all begin with this assumption in presentations of the wave theory.

https://doi.org/10.1017/S0270864700009292 Published online by Cambridge University Press

2. Show how each theory explains various optical phenomena, including the rectilinear propagation of light, reflection, refraction, diffraction, Newton's rings, polarization, etc.

3. Argue that in explaining one or more of these phenomena the particle theory introduces improbable auxiliary hypotheses but the wave theory does not. For example, light is diffracted by small obstacles and forms bands both inside and outside the shadow. To explain diffraction particle theorists postulate both attractive and repulsive forces emanating from the obstacle and acting at a distance on the particles of light so as to turn some of them away from the shadow and others into it. Wave theorists such as Young and Fresnel argue that the existence of such forces is very improbable. By contrast, diffraction is explainable from the wave theory (on the basis of Huygens' principle that each point in a wave front can be considered a source of waves), without the introduction of any new improbable assumptions. Similar arguments are given for several other optical phenomena, including interference and the constant velocity of light.

4. Conclude from steps 1 through 3 that the wave theory is true, or very probably true.

This represents, albeit sketchily, the overall structure of the argument. More details are needed before seeing whether, or to what extent, it conforms to Whewell's conditions or Mill's. But even before supplying such details we can see that the strategy is not simply to present a positive argument for the wave theory via an induction to its hypotheses and/or by showing that it can explain various optical phenomena. Whether it does these things or not, the argument depends crucially on showing that the rival particle theory has serious problems.

To be sure, neither Whewell's methodology nor Mill's precludes comparative judgments. For example, Whewell explicitly claims that the wave theory is more consilient and coherent than the particle theory. And Mill (who believed that neither theory satisfied his crucial inductive step) could in principle allow the possibility that new phenomena could be discovered permitting an induction to one theory but not the other. I simply want to stress at the outset that the argument strategy of the wave theorists, as I have outlined it so far, is essentially comparative. The aim is to show at least that the wave theory is better, or more probable, than the rival particle theory.

Is the wave theorist's argument intended to be stronger than that? I believe that it is. Thomas Young, both in his 1802 and 1803 Bakerian lectures (reprinted in Crew 1900), makes it clear that he is attempting to show that hitherto performed experiments, and analogies with sound, and passages in Newton, provide strong support for the wave theory, not merely that the wave theory is better supported than its rival. A similar attitude is taken by Fresnel, whose aim is not simply to show that the wave theory is better in certain respects than the particle theory, but that it is acceptable because it can explain various phenomena, including diffraction, without introducing improbable assumptions; by contrast, the particle theory is not acceptable, since it cannot. Even review articles are not simply comparative. Although he does compare the merits of the wave and particle theories in his 1834 report, Humphrey Lloyd makes it clear that this comparison leads him to assert the truth of the wave theory. In that theory, he claims:

> there is thus established that connexion and harmony in its parts which is the never failing attribute of truth....It may be confidently said that it possesses characters which no false theory ever possessed before (1877, p. 79).[2]

Let us now look more closely at the three steps of the argument leading to the conclusion. Wave theorists who make the assumption that light consists either of waves or particles do not do so simply in order to see what follows. They offer reasons, which are generally of two sorts. First, there is an argument from authority: "Leading physicists support one or the other assumption." Second, there is an argument from some observed property of light. For example, Lloyd notes that light travels in space from one point to another with a finite velocity, and that in nature one observes motion from one point to another occurring by the motion of a body or by vibrations of a medium.

Whatever one might think of the validity of these arguments, I suggest that they were being offered in support of the assumption that light consists either of waves or of particles. This is not a mere supposition. Argument from authority was no stranger to optical theorists of this period. Young in his 1802 paper explicitly appeals to passages in Newton in defense of three of his four basic assumptions. And Brougham, a particle theorist, defends his theory in part also by appeal to the authority and success of Newton. Moreover, the second argument, if not the first, can reasonably be interpreted as an induction in Mill's sense, i.e., as claiming that all observed cases of finite motion are due to particles or waves, so in all probability this one is too.[3]

I suggest, then, that wave theorists offered grounds for supposing it to be very probable that light consists either of waves or particles. I will write their claim as

(1) $p(W \text{ or } P/O\&b) \approx 1$,

where W is the wave theory, P is the particle theory, O includes certain observed facts about light including its finite motion, and b is background information including facts about modes of travel in other cases. ($\approx$ means "is close to.")

This is the first step in the earlier argument. I will postpone discussion of the second step for a moment, and turn to the third. Here the wave theorists assert that in order to explain various optical phenomena the rival particle theorists introduce improbable auxiliary hypotheses. By contrast, the wave theorists can explain these phenomena without introducing auxiliary hypotheses, or at least any that are improbable. Why are the particle theorists' auxiliary hypotheses improbable? And even if they are, how does this cast doubt on the central assumptions of the particle theory?

Let us return to diffraction, which particle theorists explained by the auxiliary hypothesis that attractive and repulsive forces emanate from the diffracting obstacle and act at a distance on the light particles bending some into the shadow and others away from it. By experiment Fresnel showed that the observed diffraction patterns do not vary with the mass or shape of the diffracting body. But known attractive and repulsive forces exerted by bodies do vary with the mass and shape of the body. So Fresnel concludes that the existence of such forces of diffraction is highly improbable. Again it seems plausible to construe this argument as an inductive one, making an inference from properties of known forces to what should be (but is not) a property of the newly postulated ones. Fresnel's experiments together with observations of other known forces provide inductive reasons for concluding that the particle theorists' auxiliary assumption about attractive and repulsive forces is highly improbable.

Even if this is so, how would it show that other assumptions of the particle theory are improbable? It would if the probability of the auxiliary force assumption given the other assumptions of the particle theory is much, much greater than the probability of this auxiliary assumption not given the rest of the particle theory, i.e., if

(2) $p(A/P\&O\&b) >> p(A/O\&b)$,

where A is the auxiliary assumption, O includes information about diffraction patterns and Fresnel's experimental result that these do not vary with the mass or shape of the diffractor, b includes information about other known forces, and >> means "is much, much greater than." If this condition is satisfied, it is provable that the other assumptions of the particle theory have a probability close to zero,[4] i.e.,

(3) $p(P/O\&b) \approx 0$.

Although wave theorists did not explicitly argue for (2) above, they clearly had grounds for doing so. If by the particle theory P light consists of particles subject to Newton's laws, and if by observational results O light is diffracted from its rectilinear path, then by Newton's first law a force or set of forces must be acting on the light particles. Since the light is being diffracted in the vicinity of the obstacle, it is highly probable that this obstacle is exerting a force or forces on the light particles. That is, with the assumptions of the particle theory, auxiliary hypothesis A is very probable. However, without these assumptions the situation is very different. Without them the fact that other known forces vary with the mass and shape of the body exerting the force, but diffraction patterns do not, makes it unlikely that such forces exist in the case of diffraction. Or at least their existence is much, much more likely on the assumption that light consists of particles obeying Newton's laws than without such an assumption, i.e., (2) above. An important part of the argument here is inductive, based as it is on information about other mechanical forces.

From (1) and (3) we infer:

(4) $p(W/O\&b) \approx 1$,

that is, the probability of the wave theory is close to 1, given the background information and certain optical phenomena, including diffraction.

Now we can return to the second step of the original argument, the one in which the wave theorist shows that his theory can explain a range of optical phenomena, not just the finite velocity of light and diffraction. What inferential value does this have? The wave theorist wants to show that his theory is probable not just given some limited selection of optical phenomena but given all known optical phenomena. This he can do if he can explain these phenomena by deriving them from his theory. Where $O_1,\ldots,O_n$ represent known optical phenomena other than diffraction and the constant velocity of light -including rectilinear propagation, reflection, refraction, and interference -if the wave theorist can derive these from his theory, then the probability of that theory will be at least sustained if not increased. This is a simple fact about probabilities.

Accordingly, the explanatory step in which the wave theorist derives various optical phenomena $O_1,\ldots,O_n$ from his theory permits an inference from (4) above to:

(5) $p(W/O_1,\ldots,O_n \&O\&b) \approx 1$,

i.e., the high probability of the wave theory given a wide range of observed optical phenomena. This is the conclusion of the wave theorist's argument.

If the explanation of known optical phenomena sustains the high probability of the wave theory without increasing it, does this mean that such phenomena fail to constitute evidence for the wave theory? Not at all. According to a theory of evidence I

https://doi.org/10.1017/S0270864700009292 Published online by Cambridge University Press

have developed (Achinstein 1983, chs. 10-11), optical phenomena can count as evidence for the wave theory even if they do not increase its probability. I reject the usual increase-in-probability account of evidence in favor of conditions that require the high probability of the theory T given the putative evidence O_i, and the high probability of an explanatory connection between T and O_i, given T and O_i. Both conditions are satisfied in the case of the wave theory.

In formulating the steps of the argument in the probabilistic manner above, I have clearly gone beyond what wave theorists say. For one thing, they do not appeal to probability in the way I have done. More importantly perhaps, while they argue that auxiliary hypotheses of the particle theorists are very improbable, they do not say that these assumptions are much more probable given the rest of the particle theory than without it. The following points are, I think, reasonably clear. (i) Wave theorists suppose that it is very likely that the wave or the particle theory is true, an assumption for which they have arguments. (ii) They argue against the particle theory by criticizing auxiliary assumptions of that theory, which introduce forces (or whatever) that violate inductively supported principles. (iii) Wave theorists argue that their theory can explain various optical phenomena without introducing any such questionable assumptions. (iv) Their reasoning, although eliminative, is different from typical eliminative reasoning; their first step is not to canvass all possible theories of light, but only two, for which they give arguments; their reasoning is not of the typical eliminative form "these are the only possible explanations of optical phenomena, all of which but one lead to difficulties." Reconstructing the wave theorists' argument in the probabilistic way I have done captures these four points. Whether it introduces too many fanciful ideas is a question I leave for my critics.

Is the argument Whewellian or Millian? It does satisfy the first three of Whewell's conditions. It invokes the fact that various optical phenomena are derived from the wave theory. These include ones that prompted the theory in the first place (rectilinear propagation, reflection, and refraction), hitherto unobserved phenomena that were predicted (e.g., the Poisson spot in diffraction), and phenomena of a kind different from those that prompted it (e.g., diffraction, interference, polarization). The argument does not, however, satisfy Whewell's fourth condition. It does not appeal to the historical tendency of the theory over time to become simpler and more coherent. But the latter is not what divides Whewell from Mill. Nor is it Whewell's first three conditions, each of which Mill allows for in the ratiocinative part of his deductive method. Mill's claim is only that Whewell's conditions are not sufficient to establish the truth or high probability of an hypothesis. They omit the crucial first step, the inductive one to the hypothesized causes and laws.

As I have reconstructed the wave theorists' argument, an appeal to the explanatory power of the theory is a part, but not the whole, of the reasoning. There is also reasoning of a type that Mill would call inductive. It enters at two points. It is used to argue that light is most probably composed either of waves or of particles (e.g., the "finite motion" argument of Lloyd). And it is used to show that light is probably not composed of particles, since auxiliary hypotheses introduced to explain various optical phenomena are very improbable. This improbability is established by inductive generalization (e.g., in the case of diffraction, by inductively generalizing from what observations and experiments show about diffraction effects, and from what they show about forces). My claims are that wave theorists did in fact employ such inductive reasoning; that with it the argument that I have constructed is valid; and that without it the argument is invalid, or at least an appeal to Whewell's explanatory conditions is not sufficient to establish the high probability of the theory (though this last claim requires much more than I say here; see Achinstein 1991, Essay 4).

4. Explanatory Anomalies

One objection critics of my account may raise is that it does not do justice to explanatory anomalies in the wave theory. That theory was not able to explain all known optical phenomena. Herschel (1845), e.g., notes dispersion as one such phenomenon - the fact that different colors are refracted at different angles. Now the wave theorist wants to show that his theory is probable given all known optical phenomena, not just some favorable subset. But if dispersion is not derivable from the theory, and if there is no inductive argument from dispersion to that theory, then on the account I offer, the wave theorist cannot reach his desired conclusion. He can say only that his theory is probable given other optical phenomena. And he can take a wait-and-see attitude with respect to the unexplained ones. This is essentially what Herschel himself does in the case of dispersion.[5]

Let me now say how wave theorists could in principle deal with such anomalies that relates to the probabilistic reconstruction I offer. The suggestion I will make is, I think, implicit in their writings, if not explicit. And, interestingly, it is a response that combines certain Whewellian and Millian ideas. In what follows, I restrict the anomalies to phenomena which have not yet been derived from the wave theory by itself or from that theory together with auxiliary assumptions whose probability is very much greater given the wave theory than without it.

As Cantor notes in his very informative book *Optics after Newton*:

> Probably the central, and certainly the most repeated, claim [by the 1830's] was that in comparison with its rival the wave theory was more successful in explaining optical phenomena (Cantor 1983, p. 192).

Cantor goes on to cite a table constructed in 1833 by Baden Powell, a wave theorist, listing 23 optical phenomena and evaluating the explanations proposed by wave and particle theories as "perfect," "imperfect," or "none." In the no-explanation category there are 12 entries for the particle theory and only 2 for the wave theory; while there are 18 "perfects" for the wave theory and only 5 for the particle theory.

Appealing, then, to the explanatory success of the wave theory, a very simple argument is this:

(6) Optical phenomena $O_1,...,O_n$ can be coherently explained by the wave theory.
O is another optical phenomenon.
So probably
O can be coherently explained by the wave theory.

By a "coherent" explanation I follow what I take to be Whewell's idea: either the phenomenon is explained from the theory without introducing any additional assumptions, or if they are introduced they cohere both with the theory and with other known phenomena. In particular, no auxiliary assumption is introduced whose probability given the theory is very high but whose probability on the phenomena alone is low. Or, more generally, no such assumption is employed whose probability on the theory is very much greater than its probability without it.

Commenting on argument (6), the particle theorist might offer a similar argument to the conclusion that the particle theory can also explain O. But this does not vitiate the previous argument. For one thing, by the 1830's, even though Powell's table was not constructed by a neutral observer, it was generally agreed that the number of optical phenomena known to be coherently explainable by the wave theory was considerably greater than the number explainable by the particle theory. So the wave theorist's argument for his conclusion would be stronger than the particle theorist's for his. But even more importantly, the conclusion of the argument is only that O can be coherently explained by the wave theory, not that it cannot be coherently explained by the particle theory. This is not eliminative reasoning.

Argument (6) above might be construed in Millian terms as inductive: concluding "that what is true of certain individuals of a class is true of the whole class," and hence of any other particular individual in that class (Mill 1959, p. 188; see note 3 above). Mill's definition is quite general and seems to permit an inference from the explanatory success of a theory to its continued explanatory success. Indeed, in his discussion of the wave theory he notes that "if the laws of propagation of light accord with those of the vibrations of an elastic fluid in as many respects as is necessary to make the hypothesis afford a correct expression of all or most of the phenomena known at the time, it is nothing strange that they should accord with each other in one respect more" (Mill 1959, p. 329). Mill seems to endorse this reasoning. What he objects to is concluding from it that the explanation is true or probable.

Argument (6) might also be construed as exhibiting certain Whewellian features. Whewell stresses the idea that a theory is an historical entity which changes over time and can "tend to simplicity and harmony." One of the important aspects of this tendency is that "the elements which we require for explaining a new class of facts are already contained in our system." He explicitly cites the wave theory, by contrast to the particle theory, as exhibiting this tendency. Accordingly, it seems reasonable to suppose that it will be able to coherently explain some hitherto unexplained optical phenomenon. The important difference between Whewell and Mill in this connection is not over whether the previous explanatory argument (6) is valid, but over whether from the continued explanatory success of the wave theory one can infer its truth. For Whewell one can, for Mill one cannot.

Let me assume, then, that some such argument as (6) was at least implicit in the wave theorists' thinking; and that it would have been endorsed by both Mill and Whewell. How, if at all, can it be used to supplement the probabilistic reconstruction of the wave theorists' argument that I offer earlier in the paper? More specifically, how does it relate to the question of determining the probability of the wave theory given all the known optical phenomena, not just some subset?

The conclusion of the explanatory success argument (6) is that the wave theory coherently explains optical phenomenon O. This conclusion is made probable by the fact that the wave theory coherently explains optical phenomena $O_1,\ldots,O_n$.

Accordingly, we have:

(7) p(W coherently explains optical phenomenon O/
W coherently explains optical phenomena $O_1,\ldots,O_n$) > k

where k is some threshold of high probability, and W is the wave theory. If we construe such explanations as deductive, then

(8) "W coherently explains O" entails that $p(W/O\&O_1,\ldots,O_n) \geq p(W/O_1,\ldots,O_n)$

So from (7) and (8) we get the second-order probability statement

(9) $p(p(W/O\&O_1,...,O_n) \geq p(W/O_1,...,O_n)/W \text{ coherently explains } O_1,...,O_n) > k$

But the conclusion of the wave theorists' argument is

(10) $p(W/O_1,...,O_n) \approx 1$,

where $O_1,...,O_n$ includes all those phenomena for which the wave theorist supplies a coherent explanation (I suppress reference to background information here). If we add (10) to the conditional side of (9), then from (9) we get

(11) $p(p(W/O\&O_1,...,O_n) \approx 1/W \text{ coherently explains } O_1,...,O_n$
and $p(W/O_1,...,O_n) \approx 1) > k$.

This says that, given that the wave theory coherently explains optical phenomena $O_1,...,O_n$, and that the probability of the wave theory is close to 1 on these phenomena, the probability is high that the wave theory's probability is close to 1 given O - the hitherto unexplained optical phenomenon - together with the other explained phenomena. If we put all the known but hitherto unexplained optical phenomena into O, then we can conclude that the probability is high that the wave theory's probability is close to 1 given all the known optical phenomena.

How is this to be understood? Suppose we construe the probabilities here as representing reasonable degrees of belief. Then the first-order probability can be understood as representing how much belief it is reasonable to have in W; while the second-order probability is interpreted as representing how reasonable it is to have that much belief. Accordingly, conclusion (11) says this:

> Given that the wave theory coherently explains optical phenomena $O_1,...,O_n$, and that it is reasonable to have a degree of belief in the wave theory, on these explained phenomena, that is close to 1, there is a high degree of reasonableness (greater than k) in having a degree of belief in the wave theory W, on both the explained and the unexplained optical phenomena, that is close to 1.

This, of course, does not permit the wave theorist to conclude that $p(W/O\&O_1,...,O_n) \approx 1$, i.e., that the probability of the wave theory on all known optical phenomena - explained and unexplained - is close to 1. But it does permit him to say something stronger than simply that his theory is probable given a partial set of known optical phenomena. It goes beyond a wait-and-see attitude with respect to the unexplained phenomena.

Notes

[1]Reprinted in Lloyd (1877). In what follows page references will be to this.

[2]Herschel in his (1845) does not take as strong a position as Lloyd, although there are passages in which he says that the wave theory is confirmed by experiments (e.g., pp. 473, 486). In his later 1830 work he is even more positive. For example:

> It may happen (and it has happened in the case of the undulatory doctrine of light) that such a weight of analogy and probability may become accumulated on the side of an hypothesis that we are compelled to admit one of two things; either that it is an actual statement of what really passes in nature, or that the

reality, whatever it be, must run so close a parallel with it, as to admit of expression common to both, at least as far as the phenomena actually known are concerned (Herschel 1987, pp. 196-7).

[3]Although Mill defines induction as involving an inference from observed members of a class to the whole class, he clearly includes inferences to other unobserved members of the class. He writes: "It is true that (as already shown) the process of indirectly ascertaining individual facts is as truly inductive as that by which we establish general truths. But it is not a different kind of induction; it is a form of the same process.... (Mill 1959, p. 186).

[4]For a proof see Achinstein 1991, pp. 85-6. It might be noted that the introduction of an auxiliary assumption with very low probability does not by itself suffice to show that the other assumptions of the theory are highly improbable.

[5]Herschel writes "We hold it better to state it [the difficulty in explaining dispersion] in its broadest terms, and call on the reader to suspend his condemnation of the doctrine for what it apparently will not explain, till he has become acquainted with the immense variety and complication of the phenomena which it will. The fact is, that neither the corpuscular nor the undulatory, nor any other system which has yet been devised, will furnish that complete and satisfactory explanation of all the phenomena of light which is desirable (Herschel 1845, p. 450).

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