To See Or Not To See: The Uses of Photometers and Measurements of Reflective Power

Xiang Chen
California Lutheran University

Armed with a photometer originally designed for evaluating telescopes, Richard Potter in the early 1830s measured the reflective power of metallic and glass mirrors. Because he found significant discrepancies between his measurements and Fresnel's predictions, Potter developed doubts concerning the wave theory. However, Potter's measurements were colored by a peculiar procedure. In order to protect the sensitivity of the eye, Potter made certain approximations in the measuring process, which exaggerated the discrepancies between the theory and the data. Potter's measurements received strong criticisms from wave theorists, not because they felt they needed to defend their theory, but because they believed that Potter was wrong in using the eye as an essential apparatus in the experiments. Potter's photometric measurements and the subsequent debate reveal the existence of two incompatible sets of measuring procedures, each of which consisted of a body of practices concerning how photometric instruments should be used properly. In the debate, the differences regarding measuring procedures shaped the participant's judgments of experimental evidence and eventually their evaluations of the optical theories.

1. Introduction

The wave theory of light was introduced to Britain in the late 1820s, and immediately embraced by a group of Cambridge-trained "gentlemen of science." In the eyes of these newly committed wave theorists, the evidence for the wave theory was overwhelming. The theory was able to explain a variety of optical phenomena by a simple model, provide quantita-

tive accounts with elegant mathematical analysis, and make successful predictions of hitherto unknown phenomena (Whewell [1837] 1967, Vol. 2, pp. 346–73). However, the wave theory did not command complete support from the British optical community. Several members of the community, including David Brewster, John Barton, Henry Brougham and Richard Potter, never accepted the wave theory. This group of wave opponents was not large, nor organized, but their voice was persistent. In Britain, a heated particle-wave debate emerged in the early 1830s and lasted until the early 1850s.[1]

Among the wave opponents, Richard Potter (1799–1868) was the most stubborn. Potter had been an amateur scientist for more than two decades since he graduated from grammar school. He went to Cambridge to obtain formal education in 1835 and graduated in 1838 as a sixth wrangler. In 1841, he became Professor of Natural Philosophy and Astronomy at University College, London, and held that position until 1865. Potter first expressed his discontent to the wave theory in several articles published in the early 1830s, in which he reported discrepancies between the wave theory and his experimental discoveries. After he graduated from Cambridge, Potter published another group of articles in the early 1840s, directly challenging the fundamental doctrines of the wave theory. He continued his battle against the wave theory until the end of the 1850s, even after Brewster had given up his objections. In 1859, Potter published the second volume of his *Physical Optics* with the subtitle *The Corpuscular Theory of Light: Discussed Mathematically,* in which he proposed a new particle theory to replace the well-established wave theory.

Potter's aversion to the wave theory indicates that he upheld a tradition that was essentially incompatible with the one accepted by his opponents. In this paper I will examine the instrumental basis of Potter's attitude toward the wave theory. Armed with a reflecting photometer originally designed for evaluating telescopes, Potter measured the reflective power of metallic and glass mirrors at various angles in the early 1830s. Becuse he found significant discrepancies between his measurements and Fresnel's predictions, Potter developed doubts concerning the wave theory. However, Potter's measurements were colored by a peculiar procedure. In order to protect the sensitivity of the eye, Potter made certain approximations in the measuring process, which exaggerated the discrepancies between the theory and the data.

---

1. For studies of the particle-wave debate in the 1840s and the early 1850s, see Cantor (1983, pp. 186–87), Buchwald (1989, pp. 296–302), Chen & Barker (1992), Chen (1997), and Chen (1998).

Potter's photometric measurements were strongly criticized by wave theorists, not because they felt that they needed to defend their theory, but because they believed that Potter was wrong in using the eye as an essential apparatus in the experiments. I will show that the differences between Potter and his critics reflected two incompatible sets of measuring procedures, each of which consisted of a body of practices concerning how photometric instruments should be used properly. These measuring procedures functioned in many ways as paradigms in the debate, shaping practitioners' judgments regarding experimental evidence and eventually their evaluations of the optical theories.

2. Potter's reflecting telescope

Richard Potter was born in Manchester on January 2, 1799. His father was at that time a corn and flour merchant, but shortly afterwards gave up that trade and became a partner in a brewery firm. In this business, Potter's father accumulated considerable wealth, and raised a large family with ten sons (Smith 1874). Potter went to the Manchester Grammar School in 1811, taking classes in the lower department. In the Manchester Grammar School, the lower department was in essence an elementary school, teaching reading and writing in English. When a student was sufficiently skilled in these subjects, which usually took about five years, he would be "promoted" to the higher department, located on the second floor of the building. The subjects in the higher department were the classics. Students first took the Usher's Latin class, and then the High Master's class, which would prepare them for the university (Graham & Phythian 1966). Potter spent four years in the lower department, and like most students who attended the lower department, he did not live in the school. When he was 16, soon to be entering the higher department, his father removed him from the school and placed him in a Manchester warehouse. He was then for more than a decade engaged in various branches of business life, but without success. He later recalled that, during this time, he devoted all of his spare time to scientific study, especially to optics and chemistry (Smith 1874).

Apparently, leaving the school to become a merchant was not Potter's own choice, but his father's decision. Most merchants in early nineteenth-century Manchester only wanted their sons to learn basic skills for business, and few allowed their sons to enter the higher department. The interruption in Potter's education offers a hint to understand Potter's early life. The grammar school only offered Potter limited subjects of study—mathematics, arithmetic, and science were not in the curriculum of the lower department until 1833. However, Potter might already have

dreamt of entering the higher department, and eventually university, during his years in grammar school. This may partly explain why he devoted all of his free time to science, which apparently had nothing to do with the life of a merchant. His interests in science may have been a part of his rebellion against his father.

Between 1819 and 1820, Potter started his first scientific project: to build a reflecting telescope. He spent more than ten years on this project, and accumulated considerable knowledge. In 1831, he was so proud of his experience that he published an article in *Edinburgh Journal of Science,* offering tips and hints to amateurs who were also interested in building reflecting telescopes. The key components of Potter's reflecting telescope were metallic mirrors. Potter first asked a local bell-maker to cast the mirrors for him, but he later cast the mirrors himself. To improve the hardness of the mirrors, Potter used a special technique of chilling the metals as soon as the casting was formed, which had been recommended by John Edwards in the late eighteenth century. The most difficult step in making these mirrors, Potter recalled, was the task of polishing. At the beginning, Potter used common polishing powders available in shops, such as putty (oxide of tin) and rouge (oxide of iron), but he soon found them unsatisfactory. For example, commercial oxide of iron was always mixed with carbonate of iron, which corroded surfaces and reduced the quality of the result. In order to prepare better polishing powder, Potter spent two years studying chemistry with John Dalton as his tutor (probably in the early 1820s). Finally, Potter learned a method for producing pure oxide of iron from copperas (sulphate of iron), and obtained satisfactory mirrors (Potter 1831*c*).

Potter continued to have close contact with Dalton until he left for Cambridge in 1834. Potter must have attended some of Dalton's public lectures, given in Manchester in 1820, 1825, 1827, 1828, and 1829. In these lectures, Dalton covered many topics of physics and chemistry and specifically discussed the "nature and properties of light" (Thackray 1972). Potter accepted many of Dalton's opinions on scientific subjects and shared more with chemists than physicists regarding the nature of light. In his earlier years, for instance, he considered "light and caloric as the same matter in different circumstances, and reflection as caused by an atmosphere of caloric retained around bodies by this attraction" (Potter 1831*a*, p. 54).

Potter's reflecting telescope was Newtonian, which used a concave metallic mirror to produce images and a small plane metallic mirror, inclined 45 degrees to the axis, to reflect images to the side for observation. According to the available data, Potter's reflecting telescope clearly belonged to the amateur class. The diameter of the concave mirror was only 5.5

inches, with a focal length of about 50 inches. The small plane mirror was about one by 1.25 inches. With two different eyepieces, the telescope could have two levels of magnification, either 100 or 150. Potter made many astronomical observations with this telescope. Setting it to a magnification of 100, he reported that he had seen α Geminorum distinctly defined on February 19, 1830. On the same day, he said he had seen γ Leonis to be double with a magnification power of 150 (Potter 1830).

3. Potter's reflecting photometer

The need for evaluating the telescope triggered Potter's photometric research. By the late eighteenth century, it had become common knowledge that, for the purpose of astronomical observations, magnification power was not the only standard for evaluating telescopes. A good telescope should allow observers to detect faint objects regardless of its magnification power. William Herschel called this capacity "space-penetrating power," and it depended upon three factors. The first was the aperture of the observer's pupil, which directly determined the amount of light reaching the retina. The second was the diameter of the concave mirror in a reflecting telescope or that of the objective lens in a refracting telescope. The last factor was the so-called illuminating power of the telescope, that is, the percentage of light that was transmitted through the optical system, which depended upon the reflective power of metallic mirrors or the transmitting power of glass lenses (Herschel 1800*b*, pp. 49–65).

To determine the "space-penetrating power" for his own reflecting telescopes, around 1799 Herschel conducted a series of photometric experiments to measure the reflective power of the mirrors that he used. Unlike Newtonian reflecting telescopes, Herschel's telescopes employed only a single convex mirror that reflected light at 90 degrees, and the observer obtained the image by sitting in front of the telescope. So Herschel needed to measure the reflective power of the mirror at a reflection angle of zero degrees, and to do so he used a method proposed by Pierre Bouguer in the mid-eighteenth century (Bouguer [1760] 1961, pp. 28–29).

Figure 1 illustrates the setup of Herschel's experiments. He placed the mirror to be measured halfway between two identical reflecting screens, and a lamp somewhere between the screens, along the line *AB*. From point *O,* he could see the image of the lamp in screen *A* directly and the image of the lamp in the other screen through the reflection from the mirror. He then adjusted the position of the lamp until the brightness of the two images, the direct and the reflected one, appeared to be equal. Finally, he measured the distances of the lamp to the two screens, and, according to the inverse square law, calculated the reflective power of the mirror by
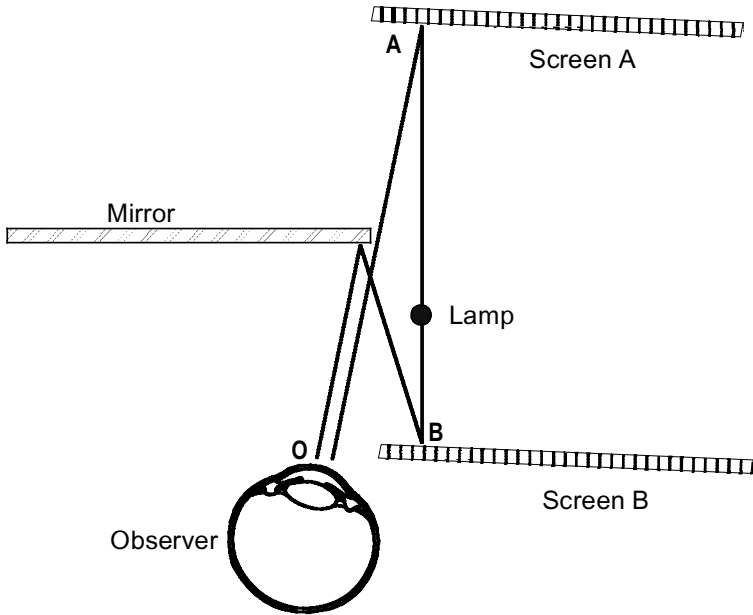
Figure 1. Herschel's apparatus for measuring reflective power.

means of the ratio of the distance squares.[2] The result showed that the reflective power of his metallic mirror was 67.262% (Herschel 1800*b,* pp. 64–65).

After he learned of Herschel's photometric research, Potter began a series of experiments to determine the reflective power of the mirrors used in his telescope. Potter did not, however, adopt Herschel's method that could measure only the reflective power near zero degrees. Because his telescope employed two mirrors, one reflecting light at normal and the other at 45 degrees, Potter needed to determine the reflective power at various angles of reflection. To achieve this task, Potter designed a special instrument, a reflective photometer (Figure 2).

The main components of this photometer were an upright screen with an aperture (four inches by 2.5 inches), and a horizontal board (4.5 inches by 50 inches) divided by a blackened partition. Unlike Herschel who used a single lamp, Potter employed two identical lamps, each of which was put on the end of a slide and placed on either side of the partition. To de-

2. The inverse square law in photometry was first stated by Kepler in the seventeenth century. But Pierre Bouguer was the first one who applied this principle to measure the reflective power of various materials around the mid-eighteenth century (Bouguer [1760] 1961, pp. 20–49).
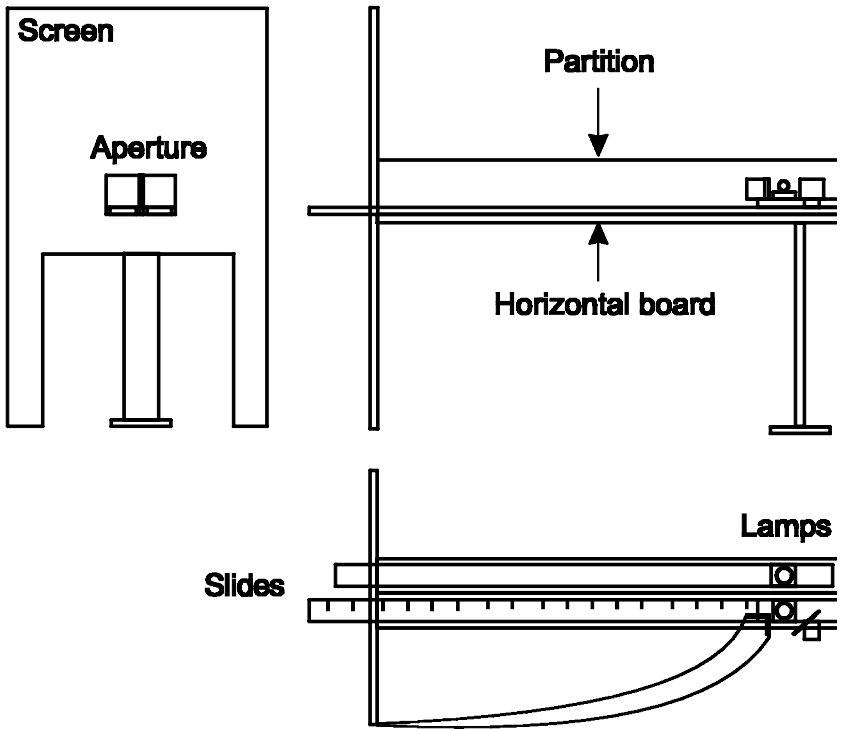
Figure 2. Potter's reflecting photometer.

termine the reflective power at various angles, Potter added special devices to the photometer. He fixed the mirror to be measured to an arm, which could be turned around an axis attached to the right-hand slide (Figure 3). To intercept alternately the direct and reflected light, Potter installed two upright partitions perpendicular to each other. When the partitions were in the direct light position as shown in Figure 3, they intercepted the reflected light; when the partitions were turned 90 degrees clockwise to the reflected light position, they stopped the direct light.

This photometer allowed Potter to directly measure the reflective power at 45 degrees, but not at zero degrees, that is, when the incident light struck along the normal to the mirror. Potter used an indirect method for the latter case. He first measured the reflective power at various angles, from 10, 20, up to 80 degrees, and then derived the value at zero by interpolation. To obtain the preset reflection angles, he adjusted the location of the lamp and the angular position of the mirror until he
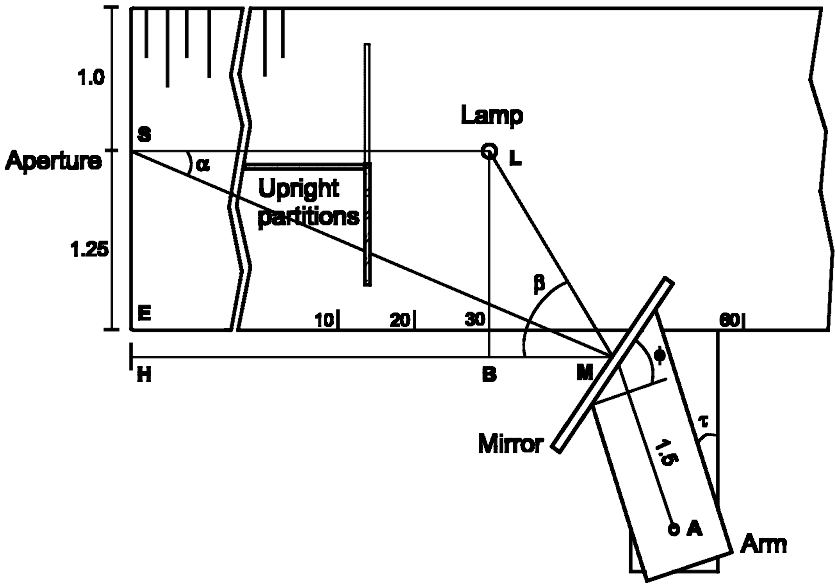
Figure 3. Potter's reflecting photometer (details).

was able to see the image of the lamp at the center of the mirror through a hole at the center of the right-hand aperture. He then determined the reflection angle by trigonometric calculations. After repeating these steps many times, he determined the positions of the lamp corresponding to all preset reflection angles and marked them in the slide.[3]

Potter later recalled that one of the major difficulties that he experienced in these experiments arose from "the fatigue of the eye experienced by looking long and intently at bright objects surrounded by darkness, which prevents it after some time judging accurately of very small differences [in brightness]"(Potter 1830, p. 279). To reduce the fatigue of the eye, Potter covered the aperture with semi-translucent paper, which reduced the contrast between the light sources and the background. Potter also invented several "remote-control" devices, which allow him to conduct the experiments without exposing himself to direct light from the lamps. He put the lamps on moveable slides, and because the ends of these slides extended over the screen, he could adjust the distances to the lamps

3. The angle of reflection would be affected by the variation in the distance of the mirror to the screen during the experiment. Potter probably used a method of trial and error to estimate this distance before he took the above steps to determine the reflection angles. In this way, later changes in the distance of the mirror to the screen would only shift the focus of the reflected light slightly out of the center of the aperture.

by simply pulling or pushing the slides while staying behind the screen. He marked the right-hand slide with divisions, in .25 inch intervals so that he could determine the distance between the lamp and the screen by simply reading off the divisions. By attaching strings to the corners of the perpendicular partitions, he could turn them in either direction without leaving his seat behind the screen.

4. Potter's measurements of metallic mirrors

Using the specially designed photometer, Potter began to measure the reflective power of several metallic mirrors, one composed of cast steel and the rest of tin-copper alloy. The crucial step in Potter's measuring process was to use the eye to match brightness on the aperture. The accuracy of this procedure obviously relied upon the sensitivity of the eye, which, according to Bouguer, could detect differences in brightness as small as 1.5% (Bouguer [1760] 1961, pp. 50–51).[4] To begin with, Potter put the right-hand lamp and the mirror in preset positions and turned the perpendicular partitions to stop the reflected light. He then made the first brightness match, adjusting the left-hand lamp until equal brightness appeared in the aperture, and measuring the distance between the right-hand lamp and the screen (the distance of the direct light). Next, he turned the partitions to stop the direct light, and made the second brightness match by pulling the right-hand slide together with the lamp and the mirror closer to the screen until equal brightness appeared in the aperture. He again measured the distance between the right-hand lamp and the screen (the distance of the reflected light). Finally, with the distance of the direct light (D_{dir}) and the distance of the reflected light (D_{ref}), he calculated the reflective power (P) by using the following equation derived from the inverse square law:

$$P = \left(\frac{D_{ref}}{D_{dir}} \right)^2$$

Among these operations, the measurement of distance deserves our attention. Potter's measurement of the distance of the direct light was straightforward. He obtained this parameter by simply reading off the divisions on the slide. But Potter's method of measuring the distance of the reflected light was peculiar. This parameter is the sum of the distance from the lamp to the mirror (*LM* in Figure 3) and the distance from the mirror

4. Helmhotz later found that, with better designed matching fields, the eye could detect brightness difference as small as .075% (Palaz 1896, p. 11).

to the center of the aperture (*MS*). The value of *LM* was available before the experiment from the preset positions of the lamp and the mirror, but the value of *MS* was not, because after the second brightness matching, the reflected light no longer fell into the center of the aperture. Potter made it clear that he did not actually measure *MS*. "It will be seen that the divisions commencing only at the thicker piece of wood, the distance of the lamp in the direct measurements, and the sum of the distances of the lamp to the mirror, and the mirror to the commencement of the divisions, must be added afterwards in the reflected ones," he said (Potter 1830, p. 286). In other words, Potter made an approximation by substituting for *MS* the horizontal span between the mirror and the screen (*MH*), which was available by reading off the slide. The reason to make this approximation was to protect the eye. If Potter had measured *MS* directly, he would have exposed himself to direct light from the lamps and quickly developed eye fatigue. This approximation, however, did not have any notable effect on the measurements of metallic mirrors. Because metals had relatively high reflective power, the right-hand lamp was still quite far away from the screen after the second brightness matching, usually more than 30 inches. Potter's approximation of distance caused only about .1% deviation in the final measurements.

Potter's calculations also deserve our attention. Potter knew that if the light from the source did not fall onto a surface perpendicularly, the illumination of the surface would be proportional to the cosine of the incident angle α. This was the cosine law of illumination found by Johann Lambert in the late eighteenth century. In Potter's experiments, the reflected light was not perpendicular to the screen. Thus, the reflective power should have been calculated using the following equation:

$$P = \frac{1}{\cos \alpha} \times \left(\frac{D_{ref}}{D_{dir}} \right)^2$$

where α is the angle between the reflected light and the normal of the screen. But as with *MS*, α had to be measured experimentally. For the same reason of protecting the eye, Potter again approximated: he completely ignored the incident angle in his calculations. Fortunately, this approximation also did not cause significant degradation of the accuracy in the metallic experiments. Due to the high reflective power of metals, the incident angles in Potter's metallic experiments were always close to zero.

Potter first determined the reflective power of an alloy mirror at 45 degrees. After 18 measurements, he averaged the findings, which yielded 64.9%. To determine the reflective power at zero degrees, Potter first took

measurements at those preset angles and then interpolated. The results showed that the reflective power of the alloy mirror was 72.3% when the incident light was perpendicular to the mirror. These results were consistent with those given by Bouguer and Herschel.[5] According to these measurements, Potter estimated that his reflecting telescope was able to transmit about 43% of the incoming light, the same level as other Newtonian-type telescopes.

Potter's photometric measurements immediately drew the attention of many in the optical community. Brewster first heard of Potter's measurements in 1830, and quickly invited Potter to publish his results in the *Edinburgh Journal of Science,* which he edited (Smith 1874). Apparently, Brewster believed that Potter's measurements were useful for constructing reflecting telescopes. In *A Treatise on Optics* printed in 1831, Brewster cited Potter's results in the section on reflecting telescopes, and proposed to use an achromatic prism to replace the plane metallic mirror in traditional reflecting telescopes (Brewster 1831).

The impact of Potter's metallic measurements went beyond telescopic design. Repeating his measurements with different metallic mirrors, Potter found that metals reflected less light when the reflection angle increased. For example, the reflective power of a steel mirror was 57.19% at 10 degrees, dropped to 55.52% at 20 degrees, further to 53.29% at 50 degrees, but rebounded to 54.67% at 60 degrees.[6] This was a novel discovery, which invalidated the received view that, as with other substances, metals reflected more light when the reflection angle increased. Potter's discovery stimulated James MacCullagh to study metallic reflection and to discover in 1836 an empirical law to describe the reflective power of metals (MacCullagh [1836] 1880, p. 61).[7]

5. Potter's measurements of glass mirrors

Once he knew the illuminating power of his reflecting telescope, Potter wanted to make general comparisons of the quality of reflecting telescopes and refracting telescopes. He claimed that "I feel it incumbent upon me,

5. For example, Bouguer reported that the reflective power of mercury was 66.6% at 21 degrees, and 70% at 3 degrees (Bouguer [1760] 1961, pp. 93, 53).

6. Potter's measurements were surprisingly accurate. The discrepancies between Potter's measurements and those obtained by Drude in the late nineteenth century are very small, most less than 5%. For more about Drude's measurements, see Ditchburn (1991, pp. 444, 448).

7. Without making any specific theoretical assumption, MacCullagh was not able to explain metallic reflection. But it was on his empirical law that later works built the theory which is now accepted. For more on MacCullagh's work on metallic reflection and later developments, see Whittaker (1951, pp. 125–167).

. . . , to remove a very incorrect idea which is universal in the scientific world on the comparative illuminating powers of reflecting and refracting telescopes" (Potter 1831c, p. 25). The traditional belief at the time was that a reflecting telescope with two metallic mirrors had only about one-half of the illuminating power of an achromatic refracting telescope with the same aperture size. According to Potter, this belief resulted from an overestimation of glass's capacity to transmit light. To correct this misconception, Potter found a six-foot achromatic telescope made by Dollond and measured the amount of light transmitted through its objective lens. Using the same photometer, Potter began with a setting in which light from both lamps fell directly on the aperture and generated equal brightness. He then placed the objective lens of the Dollond telescope on the left-hand board, between the lamp and the screen. The inserted lens absorbed and reflected some portion of the light, so that the right-hand lamp had to be pushed away a little in order to maintain equal brightness on the aperture. With the original and adjusted distances of the right-hand lamp to the screen, Potter used the inverse square law to calculate the percentage of light transmitted through the lens. The result showed that a significant amount of light was lost due to reflection and absorption and that the lens transmitted only about 66% of the incoming light, about the same as the amount reflected by a metallic mirror. Potter thus concluded that, "an achromatic telescope with one object and one eyeglass has no advantage over a reflector in respect of light, with one speculum and one eyeglass of the same quantity of available reflecting aperture, which it has of refracting" (Potter 1831c, p. 26). Since it was relatively easy and inexpensive to increase the diameter of metallic mirrors—which was another factor affecting the space-penetrating power—Potter concluded that reflecting telescopes, particularly Herschel's front-view type that used only one concave mirror, were better choices than refracting telescopes for astronomical observations.[8]

The measurements of the achromatic lens drew Potter's attention to the absorption of glass. To determine the role of absorption in affecting the quality of lenses, he needed to know the amount of light reflected by glass. Thus, in late 1830 Potter started a new series of experiments to measure the reflective power of glass.

8. Potter also used his photometric measurements to justify his specific design of the reflecting telescope that used two metallic mirrors. In order to reduce the loss of light, Newton suggested using a convex prism to replace the plane metallic mirror in reflecting telescopes. After conducting a series of experiments to measure the amount of light transmitting through flint prisms, Potter concluded that Newton's suggestion did not greatly surpass his design in terms of illuminating power, but came with a much higher price tag (Potter 1832).

Potter used the same photometer and followed essentially the same procedures as those adopted in the metallic experiments. In the glass experiments, however, he had to place the right-hand lamp very close to the screen during the second brightness matching because of the low reflective power of glass. A significant amount of light scattered by the parts surrounding the lamp reached the aperture and inflated the measurements. Thus, Potter added a new procedure to estimate the amount of the scattered light and then subtract it from the gross readings including both the reflected and the scattered light. He started with a setting in which light reflected by the glass mirror and scattered by the surrounding parts all reached the aperture. He attached a roughly ground glass plate in front of the left-hand lamp, and adjusted the luminous area of the plate (by covering it with pieces of black paper) until equal brightness appeared in the aperture. Next, he removed the glass mirror from the photometer so that only scattered light reached the aperture, and reduced the luminous area of the glass plate in the left-hand side until equal brightness appeared. Finally, he used the ratios between the two luminous areas to determine the amount of the scattered light.

In a paper published in 1831, Potter reported his measurements of the reflective power of plate, crown, and flint glass at various reflection angles, from 10 to 80 degrees. His findings revealed several interesting features of the reflective power of glass. First, the reflective power of glass was in proportion to the angle of reflection, which was opposite to the pattern found in metals. Moreover, the reflective power of glass at small reflection angles was very low, only about 3 to 4%. Finally, the reflective power of glass remained low and changed very little when the reflection angle was less than 60 degrees, but went up rapidly afterwards.

Unlike metallic reflection for which no theoretical account was available in the early 1830s, reflection of transparent materials had been well within the domain of the wave theory since the late 1820s. Using wave theory principles, Fresnel had deduced the following formula for the amount of light (I) reflected by transparent materials:

$$I = \frac{1}{2}\frac{\sin^2\left(\theta - \theta'\right)}{\sin^2\left(\theta + \theta'\right)} + \frac{1}{2}\frac{\tan^2\left(\theta - \theta'\right)}{\tan^2\left(\theta - \theta'\right)}$$

where θ is the angle of the reflected light, and θ' is the angle of the refracted light. Potter immediately realized the theoretical implications of his photometric measurements. In late 1831, Potter published another paper in the *Edinburgh Journal of Science,* in which he claimed that, "on repetition of the experiments, I awoke to the full value of a discovery perhaps of equal importance in physical optics with any of late date, and of which I

have just reason to be highly proud, and this on several accounts; first, that I believe it is the experiment to settle the question of the rival theories on the nature of light, as to whether it is an emitted matter, or only consists of undulations or vibration in a subtile ether" (Potter 1831*b,* p. 322).

To test the wave theory, Potter used Fresnel's formula to calculate the reflective power of glass, and then compared the predictions with his measurements. The results were always higher than the measurements. For example, Fresnel's formula predicted that the reflective power of plate glass would be 4.23% at 10 degrees, 4.37% at 30 degrees, 6.02% at 50 degrees, and 17.41% at 70 degrees, but Potter's measurements were 3.66%, 4.09%, 5.57%, and 14.06% respectively. In most cases, the discrepancies were more than 10 percent (Figure 4). Because of these discrepancies, Potter concluded that "if the formula which they have deduced from the undulatory hypothesis are found to give results at variance with observed phenomena, we are just entitled to draw an argument from it, against the hypothesis from which they emanated, as being also at variance with fact" (Potter 1831*b,* p. 323).

Potter's confidence that his measurements could offer a crucial test for the wave theory came partly from trust in his instrument, which had yielded reliable measurements in metallic experiments, and partly from the magnitudes of the discrepancies. As shown by Bouguer, photometric measurements always had their limits because the eye could not detect differences in brightness smaller than 1.5%. Since Potter's measuring procedures involved two brightness matching operations, Potter's measurements had a minimal error margin of 3%. But Potter's data showed that the discrepancies between the measurements and the predictions persisted even after the errors caused by the eye were taken into consideration.

It is important to note that a peculiar procedure that Potter first adopted in the metallic experiments and carried over to the glass experiments directly caused the lower measured results: namely, that Potter continued to approximate the reflected distance and the incident angle. In the metallic experiments, the impact of these approximations was negligible, but their consequences became significant in the glass experiments. Due to its low reflective power at small reflection angles, Potter had to pull the glass to be measured very close to the aperture in the second brightness matching, for instance, only about six inches away from the aperture at 10 degrees. In this setting, the approximation for the reflected distance was about 2% lower than the true value, and the incident angle was more than 13 degrees. Thus, without the approximations, Potter's glass measurements would have been higher. Using the experimental data offered by Potter, we can estimate the true values of the reflected distance and the incident angle, and then recalculate the reflective power at various

Plate glass (n=1.517)	Angle of reflection							
	10	20	30	40	50	60	70	80
Potter's measurements	3.66	3.74	4.09	4.40	5.57	8.0	14.06	34.57
Fresnel's predictions	4.225	4.248	4.370	4.808	6.016	9.198	17.41	39.05
Discrepancy (%)	15.31	13.5	6.9	9.2	7.9	14.9	23.9	12.9

Figure 4. Comparisons between Potter's measurements and Fresnel's predictions.

Plate glass (n=1.517)	Angle of reflection				
	10	20	30	40	50
Potter's measurements	3.66	3.74	4.09	4.40	5.57
Without approximations	3.944	3.954	4.278	4.583	5.763
Fresnel's predictions	4.225	4.248	4.370	4.808	6.016
Original discrepancy (%)	15.3	13.5	6.9	9.2	7.9
Adjusted descrepancy (%)	7.1	7.4	2.2	4.9	4.4

Figure 5. A recalculation without Potter's approximations.

angles.[9] Recalculations show that the discrepancies between Potter's measurements and Fresnel's predictions would indeed have been smaller if Potter had not approximated. In the case of plate glass, the discrepancies would have dropped from 15% to 7% at 10 degrees, from 7% to 2% at 30 degrees, and from 8% to 4% at 50 degrees (Figure 5). With a minimal error margin of 3% associated with Potter's measurements, such reductions could have substantially affected Potter's argument against the wave theory, because some of the adjusted measurements were consistent with the predictions. Thus, Potter's measuring procedures might have tainted his evaluation of the wave theory. Without the approximations, Potter might not have had a case with which to challenge the wave theory.

6. Forbes's "thermal photometer" and the debate

Potter's criticisms of the wave theory immediately caused strong reactions from wave theorists. The first response from the wave camp occurred in 1834, when Humphrey Lloyd presented his "Report on Physical Optics"

9. Assuming that Potter's measurements of the reflection angles were accurate, I use Potter's experimental report to estimate the positions of the lamp and the glass by simple trigonometric analyses. In the recalculation of the reflective power, I use the Lambert version of the inverse square law, which takes the role of the incident angle into consideration. For an example of the estimations and recalculation, see Appendix.

to the British Association. In the report, Lloyd briefly mentioned Potter's photometric measurements and cast doubt on their accuracy. Without replicating Potter's experiments, Lloyd did not have solid evidence, but he raised reasonable doubt by questioning the reliability of the eye at matching brightness, which was the crucial procedure in all photometric measurements (Lloyd [1834] 1877, pp. 74–75).

In a paper presented to the 1838 meeting of the British Association, Baden Powell picked up the issue raised by Lloyd and continued questioning the accuracy of Potter's photometric measurements. Powell used a "thought experiment" to reveal the problems of photometric experiments. He asked the audience to imagine the result of a simple experiment in which the light from a candle first fell onto a screen directly, and then a thin and clear glass plate was inserted between the candle and the screen. Since reflection took place at both surfaces of the plate, more than one half of the incident light was reflected. If the eye was reliable, Powell reasoned, we should have seen a near two-to-one difference caused by the glass plate. But Powell noted that, in our daily experience, we did not perceive such a dramatic difference. Thus, he concluded that, because the eye could not accurately judge the intensity of light, photometric measurements were unreliable and should not be used to test the wave theory (Powell 1838, p. 7). But apparently Powell did not fully comprehend the procedures of photometric measurements. In the "thought experiment," he "compared" the brightness consecutively—he first observed the illumination of the direct light and then the illumination after the reflection. This procedure violated an essential requirement of photometry, namely that illuminations must be compared simultaneously.

The major challenge to Potter came from James Forbes, Professor of Natural Philosophy at the University of Edinburgh. In a paper presented to the Royal Society of Edinburgh in 1838, Forbes used experiment to question the reliability of Potter's photometric measurements. Again, he did not replicate Potter's experiments. Instead, Forbes built his criticism on experiments in which he used a different kind of "photometer" to measure the reflection of heat, assuming that the laws of reflection for heat and those for light, if not identical, would at least be analogous. Forbes's "photometer" was in principle similar to one designed by John Leslie, who used a differential air thermometer to measure the quantity of reflected light (Leslie 1824). Unlike Leslie, Forbes employed an electric thermometer, consisting of a thermoelectric pile and a galvanometer (Figure 6). The pile contained 30 pairs of bismuth-antimony bars that generated electricity when they were heated. The galvanometer consisted of a magnetic needle hung over a flattened coil of silver-wire, and it measured the elec-
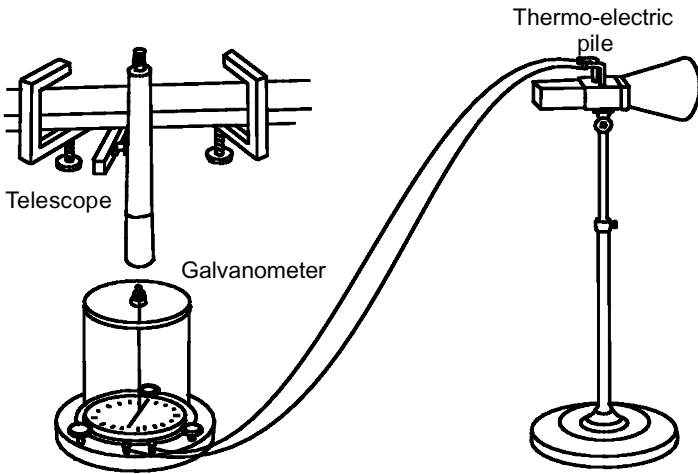
Figure 6. Forbes's "thermal photometer."

tric current in terms of the angular deviation of the needle. The extent of the angular deviation was read off in reference to the attached divided circle. With the help of a small telescope that focused upon the divided circle, Forbes was able to observe angular deviations of the needle as small as six arc-minutes, which amounted to a sensitivity of .005 centigrade degree (Forbes 1835, pp. 134–40).

Forbes used this "thermal photometer" in 1837 to measure the intensity of heat reflected by glass and found that about 8% of the heat was reflected at 55 degrees, a result close to the prediction given by Fresnel's formula (7%), assuming that Fresnel's formula could be applied to the reflection of heat. But Forbes soon realized that his measurement was invalid because he had not excluded the reflection from the second surface of the glass. Forbes improved his experiment in 1838, in which he used wedges of plate glass to exclude the reflection from the second surface. He also constructed square tubes to guide the heat rays and to reduce the impact of scattered heat from the background. Using the "thermal photometer" to measure the intensity of the source and that of the reflected heat directly, Forbes determined the reflective power of glass. He reported that the reflective power of plate glass was 4% at 10 degrees, 5.1% at 30 degrees, 7.6% at 50 degrees, and 18.5% at 70 degrees (Forbes 1851). Except for the one at 10 degrees, all of these measurements were significantly higher than Fresnel's predictions. Forbes could not say that his results verified Fresnel's formula, but he did compare his findings with Potter's

measurements and claimed that Potter must have underestimated the reflective power of glass.

Forbes also measured the intensity of heat reflected by metallic mirrors at various angles and compared his thermal measurements with Potter's photometric ones, again under the assumption that reflections of light and heat were analogous. Forbes found that his measurements verified Potter's observations that metallic reflection was less intense when the angle of reflection increased. However, Forbes also reported that the amounts of heat reflected from metallic surfaces were significantly higher than those reported by Potter. "The quantity of heat reflected by the metals is so much greater than Mr. Potter's estimate for light, as to lead me to suspect that his photometric ratios are all too small, which would nearly account for their deviation from Fresnel's law," he claimed (Forbes 1839, p. 480).

To explain the discrepancies between his measurements and Fresnel's predictions, Forbes blamed the impact of scattered heat from the background. Because scattered heat was distributed unevenly in the background, the directed heat rays from the source and the reflected heat rays from the glass could have mixed with different levels of scattered heat once they took different paths. To control the scattered heat, Forbes designed a new experiment, in which he transmitted the direct and the reflected heat rays along the same path.

The key to Forbes's proposed design was measuring the intensity of polarized heat by reflection. Partially polarized heat, or, more precisely, elliptically polarized heat, could be mathematically decomposed into two components with their planes of polarization perpendicular to one another. The two fractions in Fresnel's formula corresponded to the intensities of these two components. Fresnel's formula could then be tested by measuring the difference in intensity of polarized heat between the two components after reflection. Forbes proposed the following experiment. A beam of heat was first passed through a pile of mica sheets, which rendered the heat polarized by successive refraction. The heat rays then reached a wedge of plate glass, which reflected the incident rays to a "thermal photometer" (Figure 7). According to Fresnel's formula, the intensity of the reflected heat should be:

$$I_1 = \frac{m}{2} \frac{\sin^2(\theta - \theta')}{\sin^2(\theta + \theta')} + \frac{n}{2} \frac{\tan^2(\theta - \theta')}{\tan^2(\theta + \theta')}$$

Here, m and n were the relative intensities of the two perpendicular components in the polarized incident rays (m was the one with the plane of polarization parallel to the plane of reflection). In his previous studies,
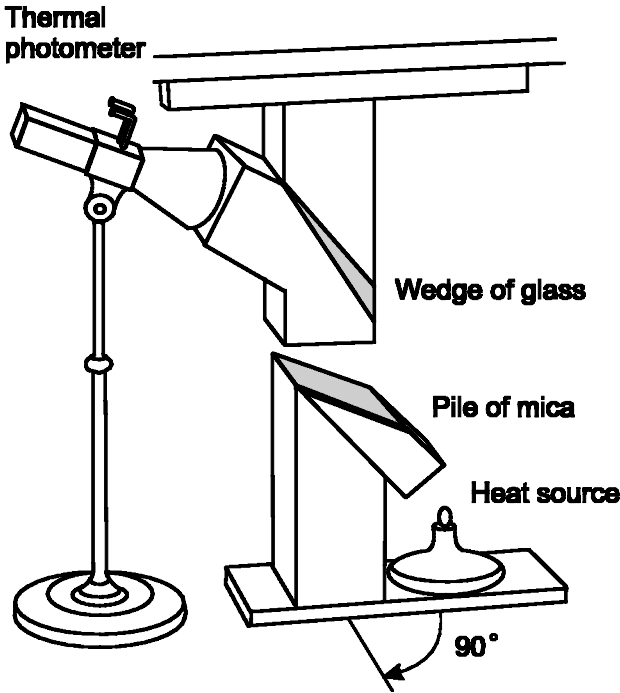
Figure 7. Forbes's proposed experiment.

Forbes had determined that the ratio of *m* to *n* was 100 to 27 in the polarized rays that passed through the mica pile (Forbes 1838, p. 551).[10] After the intensity of the reflected heat was recorded, Forbes rotated the pile of mica 90 degrees and made a new measurement. Because turning the mica pile did not alter the path of the heat rays, the scattered heat affecting the measurements should be the same in both cases. Now, according to Fresnel's formula, the intensity of the reflected heat should become:

$$I_2 = \frac{n}{2} \frac{\sin^2(\theta - \theta')}{\sin^2(\theta + \theta')} + \frac{m}{2} \frac{\tan^2(\theta - \theta')}{\tan^2(\theta + \theta')}$$

10. To determine the ratio, Forbes passed a beam of heat through two mica piles, and used the "thermal photometer" to measure the intensities of the transmitted heat when the axes of the two mica piles were parallel and perpendicular. He found that the ratio depended upon many factors, including the angle of refraction, the refracting medium, and the heat source.

The difference between these two measurements was:

$$I_1 - I_2 = \left(\frac{m-n}{2}\right)\left[\frac{\sin^2(\theta-\theta')}{\sin^2(\theta+\theta')} - \frac{\tan^2(\theta-\theta')}{\tan^2(\theta+\theta')}\right]$$

Since the values of *m* and *n* were already known, Fresnel's formula could then be tested by comparing the difference between the two fractions with the difference between the two measurements.

Forbes's design was beautiful, but he could not carry out the experiment. The obstacle was the intensity level of the reflected heat, which was too weak to be measured after both refraction and reflection. "I fear we must wait for yet more delicate instruments to measure it," he conceded (Forbes 1839, p. 480). Nevertheless Forbes insisted that his approach was better than Potter's direct visual method. Although his "thermal photometer" only measured the reflection of heat, and his verification of Fresnel's formula depended on treating radiant heat as a form of light, his approach was reliable; on the contrary, "photometric methods are so very imperfect as I still consider them to be, however dexterously employed" (Forbes 1840, p. 103). The reliability of his thermal approach came from the measuring procedure, which converted thermal effect to angular deviation and thus reduced dependence upon the eye to a minimum. In contrast, although Potter's visual photometer measured the reflection of light directly, it relied upon the eye to match brightness and thus was in essence unreliable no matter how carefully it was operated.

The criticisms from wave theorists prompted a quick response from Potter. In 1840, he published a paper in *Philosophical Magazine* defending his photometric research. Potter apparently did not understand why his critics questioned the reliability of the eye, and he did not offer any argument nor did he provide any evidence to justify the extensive use of the eye in his photometer. He instead accused his critics, particularly Lloyd and Powell, of ignorance. "As Lloyd and Powell did not think it necessary to make themselves acquainted with the subject they undertook to discuss," he claimed, "their observations do not call for any further notice in this place" (Potter 1840, pp. 17–18).

Potter devoted most of his paper to answering Forbes's criticisms. He first questioned the reliability of Forbes's measurements of reflected heat. Without experience in dealing with heat phenomena, nor the necessary skills of operating the "thermal photometer," Potter did not try to replicate Forbes's experiments and could only play with rhetoric. Potter seized upon Forbes's remark that he had experienced many "unforseen difficulties," and he insisted that because of these "unforseen difficulties"

Forbes's methods "are not likely to furnish results accurate enough for testing important laws of nature" (Potter 1840, p. 19). Responding to Forbes's suspicion that his photometric measurements were all too small, Potter offered some empirical evidence by citing the work of Michael Faraday. He gave details of Faraday's photometric measurements presented in the 1830 Bakerian Lecture on the manufacture of optical glass, in which Faraday measured the reflective power of plate, crown, and flint glass at 45 degrees. Faraday's measurements were also at odds with Fresnel's formula, and more importantly, Faraday's measurements were even smaller than Potter's. For example, Faraday reported that the reflective power of his No. 6 crown glass at 45 degrees was 4.52%, much smaller than the prediction from Fresnel's formula (5.366%). By pointing out the consistency between Faraday's and his own measurements, Potter claimed that the discrepancies between Fresnel's predictions and photometric measurements were substantial. Furthermore, Potter noted that, in effect, Faraday's photometric measurements could be used as an *experimenta crucis* to test the wave theory, because "in high refracting bodies the discordance of Fresnel's formula with experiments is palpable, for it gives results frequently one-half more, to twice as much as experiment" (Potter 1840, p. 20).

In the same paper, Potter also complained bitterly that his critics had ignored the significance of his photometric experiments and decried the criticisms of his measurements as signalling a trend in optics that blindly admired Fresnel's theory but overlooked the value of experimentation. He complained that,

> The fashion of pinning their faith on Fresnel's sleeve having become general amongst the influential in learned societies, and amongst the most eminent in mathematical attainments . . . Under such circumstance, . . . my objections to Fresnel's formula for the intensity of light reflected and transmitted by transparent bodies, although founded on laborious and careful experimental researches, have been treated as though other men's guesses were more worth than my experiments (Potter 1840, p. 17).

With a desire to find out "the truth according to the principles laid down by Lord Bacon," Potter asserted that photometry should be an experimental foundation for physical optics and proclaimed that he would continue to use it to expose the wave theory's problems.

The debate soon fell into an impasse. Potter continued to use photometric measurements to challenge the wave theory. In 1841, he published a paper in *Philosophical Magazine* targeting Airy's account for the diffraction of circular discs. Potter conducted several photometric experiments to measure the intensity of light in the center of the diffraction fringes of cir-

cular discs, and again reported significant discrepancies between Airy's predictions and his measurements (Potter 1841). But this time the wave camp remained silent. Despite Potter's claim that his experimental findings falsified the wave theory, no one from the wave camp took up Potter's challenge. Apparently, the critics believed they had convincingly discredited the photometric method after pointing out the problematic use of the eye in all such experiments.

7. Conclusion

Potter's aversion to the wave theory apparently originated from his photometric experiments. Armed with a specially designed photometer, Potter was able to measure the reflective power of metals and glass at various angles. Because he found significant discrepancies between his measurements and the theoretical predictions and because he was confident in the reliability of his own measurements, Potter rejected the wave theory. His confidence derived from the earlier successes of the photometer, which Potter had used to evaluate telescopes. For that purpose, Potter's photometer and the related experimental procedures were entirely adequate, generating results consistent with those obtained by the first-rank researchers in the field. After its success in evaluating telescopes, Potter's photometer gained a life of its own in several areas far from optics. Indeed, the testing of optical theories was only one of many new applications for the instrument, and, as the instrument evolved over time, its earlier successes justified its use in new areas.[11]

We have seen that Potter's peculiar measuring procedures had colored his judgment of the wave theory. To avoid exposure to direct light, Potter did not measure the distance in reflection and the incident angle, two important parameters in his experiments. Instead, he approximated, replacing the two parameters with substitutes that he could measure easily by reading the slide. These particular procedures affected his results by exaggerating the discrepancies between prediction and measurement. Apparently, Potter made the approximations deliberately; otherwise, he would not have explicitly noted them. In effect, his approximations were consistent with many other procedures that Potter carefully adopted in order to protect the sensitivity of the eye, including remote-control devices and a translucent aperture. Together, these procedures reflected Potter's understanding of what the role of the eye should be in photometric experiments

11. Later, photometers became important tools in astrophysics (to measure stellar magnitude) and in the illuminating gas industry (to measure the intensity of gas lighting). For more on the development of photometers in the second half of the nineteenth century, see Johnston (1996).

and of how photometers should be used. Since the eye was an intrinsic element of the photometer, protecting its sensitivity became an imperative for all such experiments.

Potter was not the only person to be concerned with the eye's sensitivity. In photometric experiments conducted during the late eighteenth and early nineteenth centuries, Bouguer, Lambert, Rumford, and William Herschel had all adopted similar procedures to reduce fatigue of the eye and to maintain its sensitivity. For instance, Bouguer took great care to adjust the distance between the matching fields, because he found that, to minimize visual fatigue, the ideal distance should reflect the anatomical features of the observer's eyes (Bouguer [1760] 1961, p. 27). Much like Potter, William Herschel used remote-control devices in his later photometric experiments in order to avoid exposure to the direct light from the lamp (Herschel 1800*a,* pp. 528–30).

These similar procedures exemplified an experimental style concerning the proper uses of photometric instruments. They reflected as well belief that the eye was an ideal photometric instrument and thus should play an essential role in all photometric experiments. In the late eighteenth and the early nineteenth centuries, many natural philosophers in Britain offered metaphysical and even theological arguments to justify the special status of the eye. For example, Peter Roget claimed that

> On none of the works of the Creator, which we are permitted to behold, have the characters of intention been more deeply and legibly engraved than in the organ of vision . . . the most profound scientific investigations of the anatomy and physiology of the eye concur in showing that the whole of its structure is most accurately and skillfully adapted to the physical laws of light, and that all its parts are finished with that mathematical exactness which the precision of the effect requires (Roget 1836, Vol. 2, p. 316).

Given this faith in the eye, several eighteenth-century photometricians regarded man-made optical instruments as, in effect, visual aids, and evaluated them according to how well they produced images suitable for perception by the eye. In practice, they adopted a set of techniques that emphasized proper use of the eye. For example, it was important to conduct optical experiments when the eye was in its best state, and it was necessary to adopt special procedures to ensure that the eye remained in its optimal condition.

Forbes, by contrast, seriously questioned the role of the eye in photometric experiments. In his measurements of reflective power, Forbes adopted procedures that were essentially incompatible with Potter's. He rejected use of the eye directly to compare and to judge brightness, and

opted instead for an indirect method that used a "thermal photometer" to measure the reflection of heat, assuming that heat behaved like light. By employing a thermoelectric pile and a galvanometer, Forbes converted the thermal effect into the angular deviation of a magnetic needle, and merely used the eye to read the scale.

Many practitioners in the optical community shared Forbes's views concerning the eye's reliability. Influenced by John Locke's demarcation between primary and secondary qualities, Whewell for example believed that the eye was in principle incapable of accurately observing secondary qualities such as light. To overcome this difficulty, Whewell suggested that the eye not be used directly to observe optical effects. The correct procedure was to convert optical properties to primary qualities, or more precisely, to geometric quantities such as linear or angular deviation, and then to measure these in reference to appropriate scales. Whewell cited Joseph Fraunhofer's measurement of refractive indices by means of prismatic spectra as an ideal example of this procedure (Whewell 1847, Vol. 1, pp. 319–28). Using a prism and an achromatic telescope, Fraunhofer first converted the optical effect (the refrangibility of light) to a group of geometric lines, and then he measured their angular positions by means of a theodolite. The eye was used merely as a locator of spatial coincidence in Fraunhofer's procedure, and the observer's subjective features no longer affected the results.

Forbes's and Fraunhofer's experimental practices, as well as Whewell's arguments, exemplified a different experimental style rooted in doubts over the eye's reliability as a judge of a quality's intensity. They did not regard the eye as a perfect model for man-made optical apparatus, nor even as an intrinsic element in any optical system. Instead, they nurtured a body of practices, both articulated and tacit, that aimed at reducing the eye's role in optical experiments, specifically by converting optical intensity to geometric coincidence.

Thus, the dispute between Potter and his critics reflected quite different styles for using photometric instruments and conducting photometric experiments. These incompatible experimental styles functioned during the dispute in many ways like such paradigms as the particle and wave traditions. By endorsing irreconcilable sets of practice concerning the uses of instruments, these styles affected processes as well as results of many photometric experiments. Eventually, they shaped some practitioners' judgments of optical theories.

If we take measuring procedures into consideration, a new aspect of the long-lived particle-wave debate in early nineteenth-century Britain begins to emerge. At first glance, the dispute between Potter and his critics was about the fate of the wave theory. Indeed, Potter used his photometric

measurements to challenge the wave theory, and all his critics came from the wave camp. But in addition to concerns about the nature of light, the discussions, exchanges and controversies on the uses of photometers constituted another important issue during the dispute. So, the long-lived particle-wave debate in early nineteenth-century Britain included development at more than one intellectual level. There was a disruptive change regarding the nature of light (from the particle model to the wave model) at the level of theory, but there were parallel developments regarding the uses of optical instruments at the level of instrumentation. There were strong interactions between theoretical paradigms and experimental styles, but developments at these two intellectual levels were independent of one another. Evolution at each level had its own pattern, determined by its own history of training, education, and practice.

This new aspect of the particle-wave debate offers an explanation for its longevity—or, at least, for Potter's nearly eternal persistence. Potter did not fully recognize the explanatory successes of the wave theory because his understanding and judgments of evidence were limited by the measuring procedure that he adopted. The accumulated development at the level of instrumentation continuously supplied materials for the debate regarding the nature of light. In fact, Potter's endless challenge to the wave theory seemed to be inevitable because of the continuity of instrumentation. Thus, we should understand Potter's aversion to the wave theory in terms of the interplay between theory and instrumentation, not of personal traits or any other non-rational factors. In general, to have a full historical and rational understanding of the long-lived particle-wave debate, we should go beyond a history of optical theories that hovers around physical models or explanatory power and adopt an inclusive historiographical perspective that appreciates as well interactions between theory and instrumentation.

Appendix: A recalculation of the reflective power without the approximations

Consider the reflection by plate glass at 30 degrees (refer to Figure 3 for the symbols).

Potter in his article gave the values of the following parameters:

$LM + MH = 8.54$ $MA = 1.5$

$SE = 1.25$ $\phi = 45°$

By means of trigonometric analyses, we learn that the remained parameters should satisfy the following conditions:

$LM^2 = (SE + EH)^2 + MB^2$ $EH = MA - (MA \times \cos \tau)$

$\beta - \alpha = 60°$ $\tau = \phi - [30° + \alpha]$

$\tan \alpha = (SE + EH) / MH$ $\tan \beta = (SE + EH) / MB$

Solving these equations, we obtain the values of the remained parameters:

$MB = 0.4599$ $LM = 1.3376$

$BH = 6.7442$ $EH = 0.006$

$\alpha = 9.89°$ $\beta = 69.89°$

$\tau = 5.11°$

Thus, the true value of the reflected distance is:

$D_{ref} = LM + [(MB + BH)^2 + (SE + EH)^2]^{1/2} = 8.6504$

The cosine of the incident angle is:

$\cos \alpha = (MB + BH) / [(MB + BH)^2 + (SE + EH)^2]^{1/2} = 0.9851$

Since Potter had given the value of the direct distance (40 inches), we can recalculate the gross reflective power with the true values of the reflected distance and the incident angle.

$$P_G = \frac{1}{\cos \alpha} x \left[\frac{D_{ref}}{D_{dir}} \right]^2 = 4.7475\%$$

Using Potter's estimation of the intensity of the scattered light ($P_s = .47\%$), we have the adjusted reflective power:

$P = P_G - P_s = 4.278\%$

References

Bouguer, Pierre. (1760) 1961. *Pierre Bouguer's optical treatise on the gradation of light.* Translated by W. Middleton. Toronto: University of Toronto Press.

Brewster, David. 1831. *A treatise on optics.* London: Longman.

Buchwald, Jed. 1989. *The rise of the wave theory of light: Optical theory and experiment in the early nineteenth century.* Chicago: The University of Chicago Press.

Cantor, Geoffrey. 1983. *Optics after Newton: Theories of light in Britain and Ireland, 1704–1840.* Manchester: Manchester University Press.

Chen, Xiang. 1997. "The debate on the polarity of light during the optical revolution." *Archive for History of Exact Sciences* 50:359–93.

———. 1998. "Dispersion, experimental apparatus, and the acceptance of the wave theory of light." *Annals of Science* 55:401–20.

———, and Peter Barker. 1992. "Cognitive appraisal and power: David Brewster, Henry Brougham, and the tactics of the emission-undulatory controversy during the early 1850s." *Studies in History and Philosophy of Science* 23:75–101.

Ditchburn, R.W. 1991. *Light.* New York: Dover.

Forbes, James. 1835. "On the refraction and polarization of heat." *Philosophical Magazine* 6:134–142; 205–214; 284–291; 366–71.

———. 1838. "Research on heat, second series." *Philosophical Magazine* 12:545–59.

———. 1839. "Memorandum on the intensity of reflected light and heat." *Philosophical Magazine* 15:479–81.

———. 1840. "Letter to Richard Taylor, Esq., with reference to two papers in the Philosophical Magazine for January, 1840." *Philosophical Magazine* 16:102-03.

———. 1851. "On the intensity of heat reflected from glass." *Proceedings of the Royal Society of Edinburgh* 2:256–57.

Graham, J., and B. Phythian. 1966. *The Manchester Grammar School: 1515–1965.* Manchester: Manchester University Press.

Herschel, William. 1800*a.* "Investigation of the powers of the prismatic colours to heat and illuminate object, with remarks that prove the different refrangibility of radiant heat." *Philosophical Transactions of the Royal Society of London* 90:255–92.

———. 1800*b.* "Experiments on the solar and on the terrestrial rays that occasion heat, with a comparative view of the laws to which light and heat, or rather the rays which occasion them, are subject, in order to determine whether they are the same or different." *Philosophical Transactions of the Royal Society of London* 90:293–326, 437–538.

Johnston, Sean. 1996. "Making light work: Practices and practitioners of photometry." *History of Science* 34:273–302.

Leslie, John. 1824. "Letter from Professor Leslie to the Editor on Mr. Ritchie's experiments on heat, and new photometer." *The Edinburgh New Philosophical Journal* 4:170–72.

Lloyd, Humphrey. (1834) 1877. "Report on the progress and present state of physical optics." Pp. 19–146 in *Miscellaneous papers connected with physical science.* Edited by Humphrey Lloyd. London: Longman.

MacCullagh, James. (1836) 1880. "On the laws of reflection from metals." Pp. 58–62 in *The collected works of James MacCullagh.* Edited by J. Jellett and S. Haughton. London: Longman.

Palaz, Adrien. 1896. *A treatise on industrial photometry.* New York: Van Nostrand.

Potter, Richard. 1830. "An account of experiments to determine the quantity of light reflected by plane metallic specula under different angles of incidence." *The Edinburgh Journal of Science* 3:278–88.

———. 1831*a.* "An account of experiments to determine the reflective powers of crown, plate, and flint-glass, at different angles of incidence; and an investigation toward determining the law by which the reflective power varies in transparent bodies possessing the property of single refraction." *The Edinburgh Journal of Science* 4:53–67.

———. 1831*b.* "Experiments relating to the reflective powers of crown, plate, and flint glass, with theoretical considerations." *The Edinburgh Journal of Science* 4:320–28.

———. 1831*c.* "On various improvements in the casting, working, &c. of specula for reflecting telescopes, with sundry hints to amateur opticians." *The Edinburgh Journal of Science* 4:13–27.

———. 1832. "Experiments to determine the reflection at the second surface of flint glass at incidences at which no portion of the rays passes through the surface." *Philosophical Magazine* 1:56–58.

———. 1840. "On photometry in connexion with physical optics." *Philosophical Magazine* 16:16–23.

———. 1841. "On the phenomena of diffraction in the centre of the shadow of a circular disc, placed before a luminous point, as exhibited be experiment." *Philosophical Magazine* 19:151–55.

Powell, Baden. 1838. "On some points connected with the theory of light." *Annual Reports of the British Association* 8:6–7.

Roget, Peter. 1836. *Animal and vegetable physiology.* Philadelphia: Carey, Lea & Blanchard.

Smith, Jeremiah. 1874. *The admission register of the Manchester school.* Manchester: The Chetham Society.

Thackray, Arnold. 1972. *John Dalton: Critical assessments of his life and science.* Cambridge, MA: Harvard University Press.

Whewell, William. (1837) 1967. *History of the Inductive Sciences.* London: Frank Cass & Co.

———. 1847. *The Philosophy of the Inductive Sciences.* London: John W. Parkers.

Whittaker, Edmund. 1951. *A history of the theories of aether and electricity.* New York: Happer & Brothers.