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Instrumental Unification: Optical Apparatus in the Unification of Dispersion and Selective Absorption

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1. Introduction

Unification has long been regarded by many, both philosophers and scientists, as a highly respectable goal of scientific research. According to a widely received account, which was proposed first by William Whewell in the 19th century, unification can establish the truth. Whewell (1847, vol.2, p.285) believed that 'when the explanation of two kinds of phenomena, distant, and not apparently connected, leads us to the same cause, such a coincidence does give a reality to the cause, . . . This coincidence of propositions inferred from separate classes of facts, is . . . one of the most decisive characteristics of a true theory . . . '. The assumption behind Whewell's admiration of unification is that a unifying theory possesses a higher degree of confirmation because of the increase in both explanatory and predictive power. Many contemporary philosophers of science, like Friedman and Glymour, also adopt this assumption and believe that unifying theories are more likely to be true (Friedman 1983, pp.241-245; Glymour 1980, pp.31-50). Following this line of reasoning, many philosophers of science define unification as a logical process that takes the form of explanation or prediction. Unification is achieved when a theory can explain two or more classes of known facts, when it can predict cases that are different from those the theory was designed to explain, or when it can predict unexpected facts.

Some recent works in both history and philosophy of science raise doubts about the Whewellian assumption that equates unification to truth discovery. In her fine analysis of the unification achieved by Maxwell's electromagnetic theory,

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Morrison (1992, pp.103-145) finds that unifying theories do not always reflect reality. For example, Maxwell's electromagnetic theory was successful in unifying optical and electromagnetic phenomena, but the mechanical model of ether that initially facilitated this unification could not be justified on the basis of experiment. Similarly, although Maxwell's electromagnetic theory unified electricity and magnetism, a key notion behind this unification, 'displacement current', also lacked physical foundation.

The purpose of this paper is to further explore the complex features of unification. On the basis of analyzing the attempts to unify dispersion and selective absorption in 19th-century optics, and particularly of examining the critical role of optical apparatus in the unification process, I suggest that unification has its material and operational aspects, and that separate phenomena can be unified not just on the basis of theories, but also on the basis of instruments.

The earliest attempts to unify dispersion and selective absorption took place in the mid-1830s when two physicists tried to construct quantitative accounts of these phenomena on the basis of Cauchy's molecular ether model. These earlier attempts were unsuccessful and not accepted by the optical community. The failure of these early unification attempts, however, was not caused by explanatory but by instrumental obstacles. I will show how the use of different instruments led to conflicting interpretations of experimental data and subsequently a debate regarding the legitimacy of the proposed theoretical accounts. I will also reveal how the early attempts failed when the debate fell into an impasse because no instrument was available for the necessary experimental replication.

The successful unification was finally achieved forty years later when Helmholtz in 1875 proposed a mechanical model that explained both dispersion and selective absorption coherently. Several breakthroughs in optical apparatus were critical to the success. I will show how new optical instruments generated a new optical phenomenon, anomalous dispersion, which eventually falsified Cauchy's old model, and how new optical instruments justified the search for a new mechanical model that could explain the phenomena coherently. More important, I will show how new optical apparatus demonstrated that there were concomitant relations between the index of refraction and the coefficient of absorption, and that it was too improbable to attribute these correlations to chance. Thus, prior to both explanatory success and theoretical unification, the phenomena of dispersion and selective absorption had been 'unified' on an instrumental basis, in the sense that the existence of causal relations between these two hitherto separate phenomena had been revealed by experimental apparatus.

2. The Earlier Unification Attempts, 1835-1839

2.1 Dispersion, selective absorption, and Cauchy's ether model

The phenomenon of dispersion (light of different colors suffering different degrees of refraction in a prism) had long been problematic for the wave theory of light. According to the doctrines outlined by Augustin Fresnel, the velocity of light as well as its refractive index depended solely upon the elasticity of the medium transmitting it. Light of every color should travel with the same velocity and have only one refractive index in a homogeneous medium. But experiments showed that within a prism light beams traveled with different velocities and had difference refractive indices according to their colors.

Beginning in 1835, Baden Powell published a series of papers in which he developed a wave account of dispersion on the basis of Cauchy's equation of motion. Cauchy's general equation of motion was a continuation of Fresnel's work, but, unlike Fresnel's equation, Cauchy's allowed every ether particle to be displaced and calculated the net force on any given ether particle caused by displacements.[1] Beginning with Cauchy's equation of motion, Powell (Powell 1836c) derived a dispersion formula, showing that light with different wavelengths (λ) could have different refractive indices (μ):[2]

$$\frac{1}{\mu^2} = A_0 - A_1 \left(\frac{1}{\lambda}\right)^2 + A_2 \left(\frac{1}{\lambda}\right)^4 - \ldots$$

Because this formula is identical to the one independently obtained by Cauchy about the same time, it is now called the Cauchy equation and cited by contemporary textbooks as a good approximation of refractive indices in regions remote from absorption.

Selective absorption (certain colors being strongly absorbed by homogeneous media but others freely transmitted through) was also problematic to the wave theory in the 1830s.[3] In terms of the interference principle, the wave theory could only account for a single absorption line in a homogeneous medium, but experiments showed hundreds and even thousands of dark lines in an absorption spectrum. To overcome this difficulty, John Tovey (1839, 1840) developed a quantitative account of selective absorption in 1839, based also on Cauchy's molecular ether model. He began with Cauchy's basic molecular equation of motion, and obtained a formula about the intensity of light in an absorption spectrum:

$$I = C_1 e^{2\varepsilon_1 x} + C_2 e^{2\varepsilon_2 x} + C_3 e^{2\varepsilon_3 x} + \ldots$$

Here constants ε_1, ε_2 and ε_3, which can be either real or imaginary, are determined in a very complicated fashion by both the medium and the wavelength. When these constants are real and negative, the intensity of transmitted light is close to

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[1] For a brief summary of Cauchy's ether dynamics and its differences from Fresnel's equation of motion, see Buchwald (1981, pp.219-25).

[2] Powell originally stated this formula in a different format. For more about the earlier version of Powell's formula, see Chen (1998, pp.403-408).

[3] For discussions of the absorption problem, see Brewster (1833, pp.360-363) and Herschel (1833, pp.401-412).

zero, indicating that light is strongly absorbed by the medium. When these constants are imaginary, the intensity of transmitted light is equal to that of the incident, indicating that light passes through the medium freely. Thus, this formula shows that light with certain wavelengths will be absorbed and a homogeneous medium can have more than one absorption line.[4]

In retrospect, Powell's and Tovey's works in the 1830s were impressive. Even today these formulas are still regarded as good approximations. Given that both formulas were derived logically from Cauchy's molecular ether model, dispersion and selective absorption could have been unified on the basis of Cauchy's theory in the 1830s. But this was not the judgment of the optical community. Neither Powell's nor Tovey's formula was accepted by contemporaries. Why did these earlier unification attempts fail?

2.2 Theodolites, telescopes, and the debate

For either Powell or Tovey to proclaim the victory of unification, they had to test and confirm their formulas first. They soon encountered unexpected difficulties that eventually aborted the unification attempts.

To test his formula, Powell first deployed two sets of measurements that had been provided by Fraunhofer: the refractive indices of seven spectral lines as seen in prismatic spectra, and their wavelengths as obtained from diffraction spectra. According to Powell, the results of the test were impressive: all of the calculated refractive indices from his formula were either identical or very close to Fraunhofer's measurements. In most cases, the agreement was accurate to the third decimal place (Powell 1835b).[5]

In 1836, Powell decided to collect his own data. He conducted a series of experiments to measure the refractive indices of various media, most of which were liquids with high refractive power. His experimental design was quite similar to Fraunhofer's, but far less sophisticated. The key apparatus was a modified theodolite, having a prism at the center of a 10-inch dividing circle (Figure 1). The prism was hollow, so that the refractive indices of liquid media could be examined. A thermometer was inserted into the prism to measure the temperature of the medium. An achromatic telescope with a power of 10 was fixed in an arm moveable around the center. The dividing circle was ruled on silver to 10', and with the help of two opposite verniers with lenses, they could be read with 10" accuracy (Powell 1836b, pp.9-11). This modified theodolite measured rather accurately the refractive angles of the spectral lines, and subsequently their refractive indices. Using this apparatus, Powell obtained the refractive indices of the seven spectral lines in 28 liquid media.

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[4] For more about Tovey's mathematical analysis, see Buchwald (1981, pp.228-30).

[5] Powell also compared his formula with the measurements made by Rudberg, who had determined the refractive indices of seven spectral lines in another ten media. The results of these comparisons, according to Powell, were also satisfactory; see Powell (1836a).

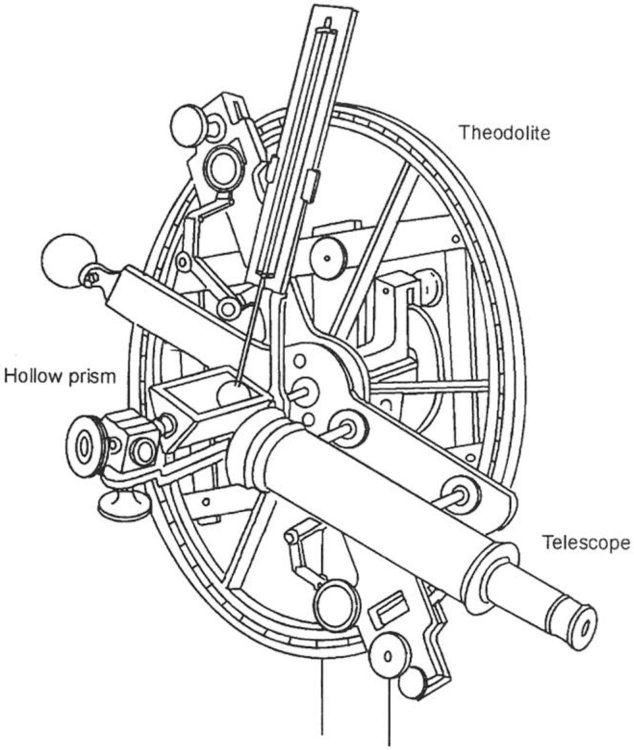

Fig. 1. *Powell's theodolite*

When Powell conducted his own experiments, he found that some spectral lines in prismatic spectra, which were single in Fraunhofer's experiments, in fact consisted of several small lines. For example, the G line, which was single in Fraunhofer's prismatic and diffraction spectra, actually consisted of a mass of small lines close together; the H line, which was also single in Fraunhofer's spectra, was actually two widely separated bands. These discoveries immediately caused trouble. Both H and G lines were single in diffraction spectra, but they now became multiple in prismatic spectra. How could these two incompatible sets of data be related so that they could be used to test the formula?

Using theodolites as the key apparatus, Powell focused his attention on angular measurements, and described the differences between his and Fraunhofer's spectra merely in terms of their angular sizes. He knew that the angular size of a spectrum was determined by the quality of the instruments -- the refractive angle and the refractive index in prisms or the density of lines in gratings. He then reasoned that the difference between his and Fraunhofer's prismatic spectra must have also been caused by the instruments. Because prisms had a higher dispersive power than gratings, particularly in the area near the violet end, spectral lines in prismatic spectra spread out in a pattern different from that in diffraction spectra. Spectral lines in Fraunhofer's diffraction spectrum, from which he determined their wavelengths, appeared 'in a form far more closely condensed together (especially toward the blue end) than they appear even in the least dispersed of the refraction-spectra'. In his prismatic spectra, however, spectral lines 'are not only far more widely separated, but those which appear single in the interference-spectra [i.e., diffraction spectra], and even in the lower dispersive media, are resolved into assemblages of several lines in the higher' (Powell 1838; original emphasis).[6]

But which one of these small lines in prismatic spectra corresponded to the single line in diffraction spectra? According to Powell, every one of them should correspond to the single line, because they all originated from the single line due to the increase of the dispersive power of the instrument. The solution then was to take the mean of these small lines to represent the whole group, so that one-to-one correspondence could be maintained for the purpose of calculation. Powell (1838) thus claimed that 'it appeared to me the only fair and reasonable method, to take the mean of the expanded set of lines as corresponding to the value of the wavelength, given for the condensed line'.

Powell's method of taking the mean, however, caused strong criticism from David Brewster. According to Brewster, both line G and H were always single even in prismatic spectra with high dispersive power, and one-to-one correspondence remained intact between prismatic and diffraction spectra. Brewster (1838) insisted that '[t]he wave length of (G) belongs positively and rigorously to the standard ray or line (G), distinctly marked in Fraunhofer's map, and distinctly characterized by precise numbers in his table; and it has nothing whatever to do with any lines near (G). In the like manner the wave length of (H) belongs positively and rigorously to the band (H), similarly marked and similarly characterized in Fraunhofer's map and tables, and it has nothing whatever to do with the band similar to (H), of which Fraunhofer has neither given the wave lengths nor measured the index of refraction'.

Brewster's criticism of Powell was based upon his own spectral experiments conducted at the beginning of 1830s. His experimental design was similar to Powell's in many aspects. A high quality prism, manufactured by Fraunhofer's company, was used to refract the sunlight emitted through an adjustable slit. An achromatic telescope was used to view the prismatic spectrum, and a wire microscope for measuring the distance between lines. Unlike Powell, Brewster did not use a theodolite; the prism, telescope and other apparatus were all independent and separated, and no angular measurements were made (Figure 2). It is important to understand why Brewster did not use a theodolite. He knew the arrangement of Fraunhofer's prismatic experiment, and a theodolite was not difficult to find. So

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[6] Powell here assumed that an increase in dispersive power should accompany an increase in resolving power. This assumption is mistaken.

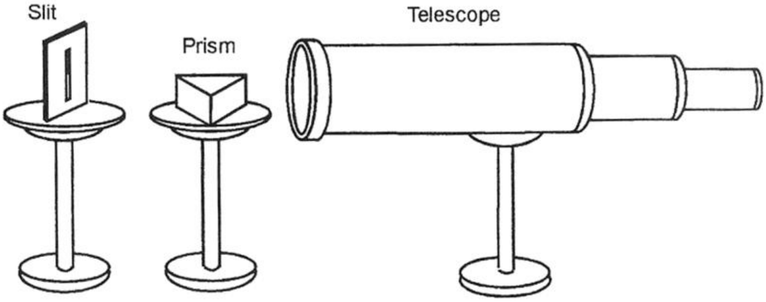

Fig. 2. *Brewster's experimental set-up*

Brewster's decision not to use a theodolite must have been deliberate. His main concern was to increase the number of spectral lines. An effective way to do so was to improve the magnifying power of the achromatic telescope by increasing its length, but a theodolite would set a limit to the size of the telescope. In his experiment, Brewster employed a 5-foot achromatic telescope made by George Dollond, the most prestigious optical instrument maker in Britain. This high-power telescope turned out to be critical -- it not only enlarged the spectrum, but also increased its resolving power. Brewster thus saw many new spectral lines. He reported that he could count more than 2,000 lines in his prismatic spectrum, most of which did not exist in Fraunhofer's original map.

Brewster had long been speculating that dark lines in spectra were caused by the absorption effects of the particles in the absorptive materials. Specifically, some particles of light must have been stopped by the material atoms in the absorptive materials but others went through. According to Brewster, 'such a special affinity between definite atoms and definite rays, though we do not understand its nature, is yet perfectly conceivable' (Brewster 1832, p.321).[7] Thus, a single spectral line could reveal the existence of a specific chemical element in the absorptive materials.

In retrospect, Brewster's effort to decompose the spectrum of a compound into the spectra of its components was sterile (James 1983). Nevertheless, Brewster's inclination to use spectra as a means of chemical analysis deeply influenced his understanding of the relations between spectral lines from different spectra. He was more interested in the chemical causation of spectral lines than in their geometrical positions, and he tried to explain the apparent differences between spectra (the number and the distribution of spectral lines) in terms of their chemical origins. According to Brewster, the discrepancies between diffraction

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7. Brewster's attempt to explain absorption by chemical affinities was unsuccessful -- it was difficult to imagine how a few elements could cause thousands of spectral lines. According to Shapiro, Brewster's unsuccessful attempt to explain absorption by affinities represented the end of a long optical tradition that appealed to chemical properties of the corpuscles of matter; see Shapiro (1993, pp.331-354).

and prismatic spectra reported by Powell must reflect differences in the chemical nature of their absorptive materials. In the case of Powell's experiment, those fine lines around G and H must have their own chemical origins. Instead of using a regular glass prism, Powell employed a hollow prism filled with liquid, which was probably the origin of those newly found fine lines. Because of different chemical origins, there was no reason to group these fine lines together by the method of taking the mean, no matter how closely these lines gathered. This explains why Brewster strongly objected to Powell's method of taking the mean: this method was fundamentally wrong because it had mixed up spectral lines that had distinct chemical natures.

2.3 Gratings and the impasse in the debate

The dispute between Powell and Brewster boiled down to a simple question: Did the G and H lines in Fraunhofer's diffraction spectrum correspond, as Powell claimed, to groups of small lines in the prismatic spectrum or, as Brewster insisted, to single lines? Both Powell and Brewster bore the burden of offering empirical evidence to support their positions, and their dispute could have been settled by carefully designed experiments. For example, Powell's position implied that new spectral lines in a diffraction spectrum would emerge from the expansion of a nearby existing line when the dispersive power of the grating increased, but Brewster suggested that they would spring out independently when new interactions between light and the absorptive materials occurred, such as the sunlight passing through thicker layers of the atmosphere. These predictions could be tested by examining the structures and positions of spectral lines in diffraction spectra under different conditions such as using gratings with different dispersive powers, or inserting different absorptive materials between the grating and the eye.[8] Thus, replicating Fraunhofer's experiments on diffraction spectra, perhaps with some minor adjustments in the experimental design such as using gratings with higher dispersive power or introducing new absorptive materials, became a necessary step to resolve the dispute between Powell and Brewster.

Replicating Fraunhofer's diffraction experiment in the 1830s was not an easy task. The key obstacle was the extremely complicated technique of making gratings. It took many years for Fraunhofer to learn how to use a diamond to rule fine lines in the surface of a glass plate covered by a layer of grease. He was able to make a grating with 3,601 lines at 8,176 lines per inch. With this grating, he

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[8] In theory, the dispute between Powell and Brewster could also be settled by examining what happened if the number of dark lines in the prismatic spectrum decreased. According to Powell, some of them should gradually condense to nearby lines when the resolving power of the prism decreased. But according to Brewster, they should simply disappear when different absorptive materials were used. However, it was impossible to reduce the resolution of prismatic spectra in practice -- the whole set of dark lines would have disappeared if the resolving power of the prism was below a certain level.

obtained diffraction spectra (the first order) with an arc of about 4.5 degrees from which the wavelengths of six prominent spectral lines could be measured (Fraunhofer 1823, p.45). The number of lines was not the only issue that determined the acceptability of gratings. Fraunhofer also noticed that all ruled lines in an acceptable grating must be identical, and that the key to ruling identical lines was the shape of the diamond point. But what should a proper diamond point look like? Fraunhofer was not sure even with the most powerful microscopes. To him, the selection of a proper diamond point depended partly upon experience and partly upon luck. Even worse, Fraunhofer kept much of the technique for making the gratings secret. Although he published parts of the technique, he never released enough information for others to replicate his work.[9]

The delicacy of gratings, together with the unarticulated features of the grating-making technique, must have deterred many in the 1830s from replicating Fraunhofer's diffraction experiment. Gratings became an obstacle that rendered the replication extremely difficult, if not impossible. This probably explains why Powell did not respond to the challenge of improving the resolution of diffraction spectra. In his study of Talbot bands, Powell reported that he had produced a diffraction spectrum by following Fraunhofer's method, but he made no effort to improve the experiment.[10] He did not provide any details of his instruments, nor the result of his experiment. Since the purpose of the experiment was to see if spectral lines in the diffraction spectrum would disappear altogether when a thin plate of glass was inserted to cover a certain area of the spectrum, Powell did not need any accurate measurement of the positions of the spectral lines. Available documents suggest that Powell's diffraction spectrum did not reach the sophisticated level of Fraunhofer's.

Brewster had also conducted some diffraction experiments but, unlike Powell, he provided detailed descriptions of the experimental results. Brewster began his diffraction experiments in 1822 when he obtained from John Barton some fine specimens of steel with grooved surfaces.[11] Using these grooved surfaces as reflection gratings, Brewster conducted his diffraction experiments. His experimental setup was somehow different from Fraunhofer's. Instead of using a narrow slit, he used a long rectangular aperture formed by nearly closing the window-shutters. The length of this aperture was about 35 degrees of arc (measured from the grating), and its width was about one degree.[12] Using a

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[9] This situation did not change until the second half of the nineteenth century, when Nobert described in detail how the shape and weight of a diamond would affect the quality of gratings. For the development of the technique of making gratings in the second half of the nineteenth century, see Dorries (1994, pp.1-36).

[10] Talbot bands are optical phenomena in which dark lines in a spectrum altogether disappear when a thin plate of glass is inserted to cover one half of the spectrum, but the dark lines remain unchanged when the thin plate covers the other half of the spectrum; see Powell (1840, pp.81-85). For the debate over Talbot bands, see Chen (1997).

[11] For more about how Barton ruled these grooved surfaces, see Grodzinski (1947).

[12] Brewster only reported the length of the aperture, which was about 30 to 40 degrees.

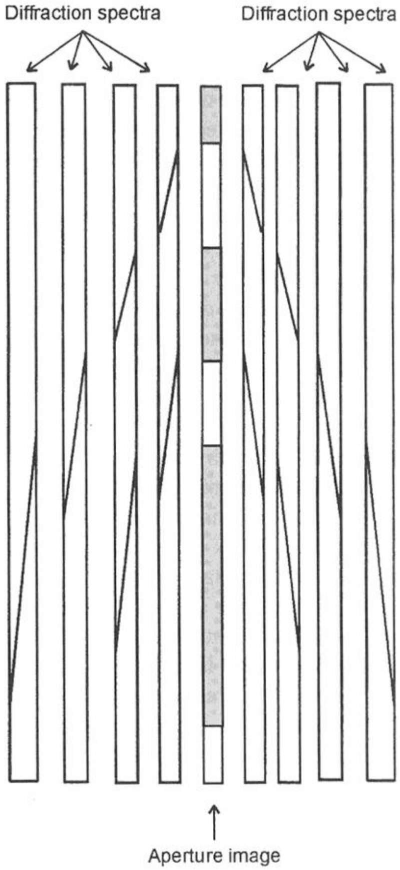

Fig. 3. *Brewster's diffraction spectra*

grooved surface with 1,000 lines per inch as a reflection grating, Brewster obtained a sequence of diffraction spectra (Figure 3). By using a source slit with a width of one degree, Brewster's diffraction spectra no longer contained any distinctive spectral lines,[13] but he found something new: there were many dark lines crossing the spectra obliquely (Brewster 1829).

To study further the nature of these oblique dark lines, Brewster felt that he needed a better grating that could improve the quality of the spectra. He had several options. For example, he could increase the density of lines in a grating by reducing the width of openings and the distance between openings, which would significantly enlarge the horizontal size of the spectra. This result, however, was not attractive to Brewster, because he could easily expand the spectra vertically by

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The width of the aperture was estimated by using the diagram drawn by Brewster (Figure 3), in which the width/length ratio of the aperture was about 1:37, according to the direct image of the aperture, AB.

13. According to Fraunhofer, only a few lines remained visible if the width of the slit exceeded one minute of arc; see Fraunhofer (1817, p.4).

increasing the length of the aperture. Another option was to reduce the distance between openings while keeping the width of openings unchanged, and consequently enhance the intensity of the spectra. For the purpose of studying those oblique dark lines, the intensity of the spectra became far more important than their angular sizes. Brewster thus asked Barton to make a grating containing 2,000 grooves per inch, in which the distance between grooves was reduced to a minimum. Barton at first agreed to make Brewster such a grooved surface, but something unexpected happened: '[Barton's] diamond point, however, having unfortunately broken before he had executed any considerable space, I was unable to make all the experiments with it which I could have wished' (Brewster 1829, p.304). In this way, a new apparatus -- a rectangular aperture -- led Brewster to study an entirely different kind of diffraction spectrum, but problems in getting necessary apparatus -- an improved grating -- soon forced Brewster to give up.

Because of the obstacles in obtaining or making high quality gratings, neither Powell nor Brewster in the late 1830s was able to improve the quality of diffraction spectra so that they could resolve their differences. The dispute between Powell and Brewster thus fell into an impasse -- neither side was able to provide evidence to verify their positions, and all subsequent exchanges between them became mainly rhetorical.

A similar problem would have occurred if Tovey had decided to test his formula of selective absorption experimentally. He would have needed measurements of both absorption and diffraction spectra, and encountered a similar difficulty in setting up one-to-one correspondence between spectra with different resolutions -- absorptive spectra contained several thousands of fine lines but diffraction spectra only several hundreds. To solve this problem, it became necessary to increase the number of spectral lines in diffraction spectra to the level of absorptive spectra. Again, this task could not be achieved in the 1830s due to difficulties in making sufficiently fine gratings.

3. The Success of the Unification, 1870-1875

3.1 Crystallized prisms and the unstable problem

In addition to the historical contingencies that hindered the earlier unification attempts, there were deep-seated difficulties that made the unification of dispersion and selective absorption on the basis of Cauchy's ether model impossible. Powell (1835a, p.266) noted that the explanation of dispersion within Cauchy's framework required an assumption regarding the structure of the medium: '*A relation between a velocity and the length of a wave is established on M. Cauchy's principle, provided the molecules are so disposed that the intervals between them always bear a sensible ratio to the length of an undulation*'. It was Fresnel who first speculated in 1822 that the account of dispersion required an assumption about the distance between the molecules in the medium, or more precisely, about the range of the molecular force. Later Cauchy further demonstrated that, if the range of the molecular force was comparable to the wavelength, then the degree of dispersion would depend essentially on the ratio of the wavelength to the range of the molecular force. On the other hand, if the range of the molecular force was much smaller than the wavelength in the void, then dispersion would not occur.[14] In this way, Cauchy's theory of dispersion implied that in homogeneous media the index of refraction increased without exception according to the frequency of the light. This implication, however, was in conflict with a novel discovery made by Fox Talbot in 1840.

According to his later testimony, Talbot conducted a series of prismatic experiments in 1840 with a very peculiar device. He spread a saturated solution of salt (double oxalate of chromium and potash) in the gap between two pieces of plane glass, and obtained a thin film. After the apparatus was set aside for a few hours, many small crystals formed in the film. Those next to the surfaces of the glass were cut away at various angles, forming many little prisms. With a candle as the light source and a card pierced with a pin hole as the aperture, Talbot was able to isolate the spectra generated by a single prism. He saw that each prism produced two spectra widely separated and oppositely polarized. One of these spectra was normal, just as those produced by glass prisms. But the other was abnormal, with colors distributed in a very strange way. The less refracted colors (red, orange, and yellow) of the spectrum were arranged normally, but the rest suffered a peculiar deviation. Instead of sitting at the more refracted side as in the regular solar spectrum, the violet and the blue located in the less refracted side of the red. In Talbot's own words, the spectrum, 'after proceeding for a certain distance, stopped short and returned upon itself' (Talbot 1871, p.409).

Even without accurate measurements, Talbot's observations of the abnormal spectra suggested that refractive indices were not always proportional to the frequencies of light, a discovery that contradicted Cauchy's theory of dispersion. If Talbot had published his experimental findings, Cauchy's theory of dispersion might have soon been questioned and rejected. However, Talbot did not announce his novel observations, because the key apparatus -- the crystallized prisms -- was not stable. After a few minutes, those crystals within the film quickly dissolved in the surrounding liquid. Later Talbot (1871, p.410) explained that 'I never published this experiment, because I found it delicate and capricious, and I was reluctant to publish any facts that might be difficult for others to verify'.

The reactions from the optical community also discouraged Talbot from publishing the discovery. Talbot described his observations of the abnormal spectra to Brewster. The reaction from Brewster, however, was quite negative. It was inconceivable for Brewster, or anyone in the 1840s who was familiar with the subject, that colors from a spectrum could be partially inverted. Brewster thus

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[14] Cauchy's demonstration was incorrect. For more on Cauchy's assumption, see Buchwald (1981, p.225).

suggested to Talbot that there must be some fallacy in the experiment. Apparently, Brewster's comments shook Talbot's own confidence to his discovery.[15] He kept silence over the next 30 years, and did not publish his observations until he read an article from C. Christiansen in 1870, who reported a similar discovery.

3.2 Hollow prisms and anomalous dispersion

Christiansen obtained abnormal spectra by means of a different experimental setup. Because the reciprocal of the refractive index of a substance is equal to the sine of its critical angle of total reflection, refractive indices can be determined by measuring the critical angles of total reflection. The advantage of this method is that it does not require a prism of the substance to be examined, and is therefore particularly useful for measuring the refractive indices of liquids. In 1870, Christiansen applied this method to examine the refractive indices of fuchsine solution (aniline red). The key apparatus in his experiment was a right-angle prism made of crown glass, which was used to generate total reflection. Christiansen spread a layer of fuchsine solution under the base (the hypotenuse) of the prism, and rested it on a horizontal table. A light beam entered the prism from the right-hand side, and was reflected at the surface of the fuchsine solution.

By examining the reflected light from the left-hand side of the prism, Christiansen saw something quite peculiar. Unlike most substances where total reflection occurred within a fairly distinct incident angle, no sharp boundary was apparent in the total reflection from the fuchsine solution. Further examination showed that the total reflection first occurred when the incidence was perpendicular to the right-hand side of the prism, and continued to exist when the angle of the incidence increased to a rather large extent. At a perpendicular incidence, the reflected light was green instead of white. When the angle of incidence was increased, the reflected light gradually changed first to (besides the green) blue, then violet, red, orange, and yellow in succession. Since an increase of the incident angle accompanied an increase of the critical angle of total reflection, Christiansen's observations revealed that the refractive indices of fuchsine solution changed according to the wavelength but in a very strange way. The refractive indices increased normally from the red up to the yellow, but dropped unexpectedly from the yellow to the blue, then increased from the blue to the violet in a normal way. Overall, the blue had the lowest value and the yellow the highest (Christiansen 1870, 1871). This discovery confirmed the observations that Talbot made 30 years ago: refractive indices did not always change in proportion to the wavelength.

Christiansen's work represented important progress in studies of dispersion.

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[15] The optical community remained skeptical when F. P. Leroux reported a similar observation in 1860. Leroux's observations were dismissed as an illusion and were soon forgotten.

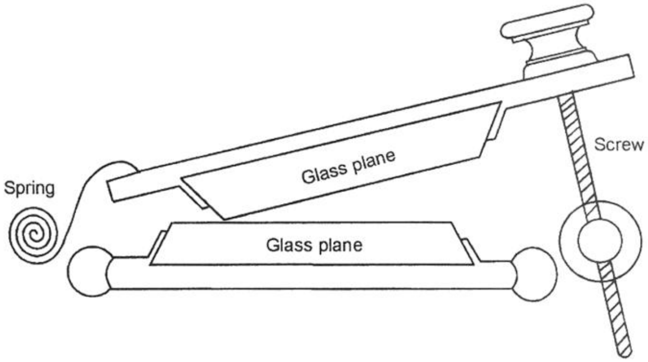

Fig. 4. *Christiansen's hollow prism*

The combination of fuchsine solution and a total-reflection prism was the first apparatus that could produce stable abnormal spectra, and thus made the verification of the discovery possible. But using the method of total reflection to examine refractive indices had a fatal defect. Because no spectral lines appeared by means of this method, no accurate measurements of refractive indices could be made. To further study abnormal spectra, Christiansen turned to the method that determined refractive indices by measuring the angular positions of spectral lines in prismatic spectra. To obtain stable prismatic spectra, Christiansen constructed a hollow prism, which was made of two pieces of plane glass inclined at an angle of about one degree (Figure 4). The angle of this prism could be adjusted easily by means of a spring and a screw attached to one of the glass planes, and the solution of fuchsine was held between the planes by capillarity. Using this hollow prism, Christiansen obtained an abnormal prismatic spectrum, which contained many distinct spectral lines and elongated to an extraordinary extent. The green light was absent in the spectrum, and the violet was the least refracted and separated from the others by a dark space. Of the remaining colors, the red, orange and yellow located in their normal order. According to the angular positions of the spectral lines, Christiansen (1871) accurately determined that refractive indices increased normally from the B line (1.450) to the C line (1.502) and then to the D line (1.561), decreased abnormally from D to F (1.312) and to G (1.258), then increased again at H (1.312). These measurements coincided with his findings by the method of total reflection.

The use of the hollow prism was a breakthrough, because it not only generated stable abnormal spectra, but also made accurate measurements of refractive indices possible. Hollow prisms soon became a powerful apparatus used by many physicists in the studies of abnormal spectra. Between 1870 and 1871, for example, August Kundt used hollow prisms to make extensive observations of abnormal spectra. The substances examined by Kundt included blue, violet, and green anilines, solution of indigo in strong sulphuric acid, carmine, permanganate of potash, and cyanine. Kundt (1871a, 1871b, 1871c) found that abnormal spectra existed widely: all substances that possessed what was known as surface colors (the color by reflection different from the color by transmission) generated abnormal spectra. Kundt thus labeled this peculiar phenomenon of dispersion 'anomalous', meaning 'uneven' etymologically, instead of 'abnormal' that implied 'contrary to law'.

Christiansen's and Kundt's systematic observations and precise measurements convincingly proved that the peculiar relations between refractive indices and wavelengths could no longer be reduced to observational or experimental errors. There was no doubt that anomalous dispersion was a genuine optical effect. Christiansen's and Kundt's findings then led to the rejection of Cauchy's theory of dispersion, which implied that refractive indices always increased according to the frequency of the light in homogeneous media.

3.3 Crossed prisms and the instrumental unification

Although hollow prisms could produce stable abnormal spectra, they did not reveal the relations between anomalous dispersion and absorption. In Christiansen's hollow-prism experiments, for example, a dark band caused by an absorption effect always appeared between the violet and the red light. In hindsight, Christiansen's experiments clear indicated that anomalous dispersion coexisted with selective absorption. But it was unclear from his experiments whether the existence of the absorption band had anything to do with the abnormal distribution of the spectral colors, and Christiansen did not offer any discussion of the possible connections between these two coexisting phenomena.

The connections between anomalous dispersion and selective absorption were first revealed by Kundt in 1872. Kundt's new instrument was a pair of crossed prisms, similar to those employed by Newton in his investigations on the refrangibility of solar light. In Newton's original design, the crossed-prism apparatus consisted of two glass prisms, the first one with its refractive edge horizontal and pointing downwards, and the second one vertical and pointing to the left of the observer (Newton 1979, pp.35-45). When a beam of sunlight passed through this apparatus, the first prism alone should form a vertical spectrum with the violet uppermost and the red below, and the second prism should displace the original vertical spectrum horizontally in proportional to the color, that is, moving the violet most and the red least. The end result was a continuous curve, showing the change of refractive indices and their relations to wavelengths in the form of geometric displacement.

In his experiment, Kundt replaced the second glass prism with a hollow one filled with a solution of cyanine, which was known to cause anomalous dispersion (Figure 5). This new apparatus generated some striking results. The second prism not only displaced the original vertical spectrum horizontally, but also divided the spectrum into two separate curves, αβ and γδ, as shown in Figure 5. These two curves indicated vividly that the order of refractive indices was disturbed -- the

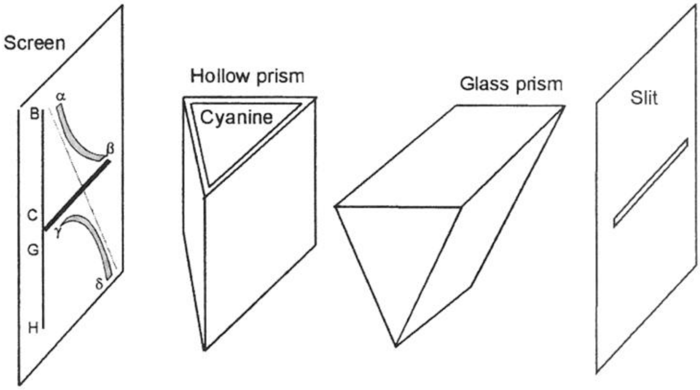

Fig. 5. *Kundt's crossed-prism experiment*

refractive index of line C was higher than that of line G. Coincident with the disturbance of the order of refractive indices, there was a strong absorption band in between the two separated curves (Kundt 1872).

Kundt repeated the experiment, filling the hollow prism with many other substances that were known to cause anomalous dispersion. He found similar results, except that sometimes there was more than one absorption band and the spectrum was divided into many fragments. After carefully examining the results of these experiments, Kundt recognized a pattern: a disruption of the spectrum was always accompanied by an absorption band. Further examinations showed that the index of refraction changed abnormally near the region of absorption. Compared to the refraction indices in a normal spectrum that were in proportion to the wavelengths (represented by the dotted line joining α and δ in figure 5), the refraction indices in Kundt's experiment increased abnormally when approaching the absorption region from the red end of the spectrum, but decreased abnormally when leaving the absorption region toward the violet end. In other words, along the direction from the red to the violet, the index of refraction increased abnormally where the coefficient of absorption raised rapidly, and diminished abnormally where the coefficients dropped rapidly -- these two parameters varied concomitantly.

The discovery of the concomitant relations between the index of refraction and the coefficient of absorption was critical. When we observe that variations of one phenomenon are always accompanied by corresponding variations in the other, there are reasons to speculate that probably these two phenomena are causally connected.[16] Of course, correlations can be simply coincidental. Even in the best scenario, correlations cannot indicate the specific form of the possible causal connection. But in this historical case, previous works on dispersion and selective absorption had indicated that it was possible to account for these phenomena in

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[16] This is called the method of concomitant variation, advocated by John Mill in the mid-nineteenth century; see Mill (1859, pp.263-66).

terms of a single theoretical model. Thus, it would be too improbable to attribute the correlation revealed by Kundt merely to chance. Although the concomitant relations did not specify whether selective absorption caused anomalous dispersion, or anomalous dispersion caused absorption, or both were effects of another common cause, they clearly suggested that causal relations existed between these two hitherto separate phenomena. At this point, dispersion and selective absorption were unified on the ground of an instrument, in the sense that the existence of causal connections between the two separate phenomena became evident.

Kundt's discovery of the concomitant relations justified the search for the hidden mechanism behind dispersion and selective absorption. Before Kundt's discovery, there was no need to unify these two phenomena. Neither Powell's nor Tovey's work in the 1830s aimed at unification -- they never believed that dispersion was in any way related to selective absorption. Kundt's discovery, however, immediately initiated many speculations about the cause behind these phenomena. Physicists began to construct various theoretical models to account for the correlations between dispersion and selective absorption.

The discovery of the existence of causal connections between dispersion and selective absorption represented the most important breakthrough in the unification of these hitherto separate phenomena. The key to Kundt's success consisted in the apparatus -- the crossed prisms. Prior to Kundt's experiments, dispersion and selective absorption were known to be coexistent, but without appropriate apparatus no one could recognize their relations. For example, because Christiansen's hollow prism exhibited the variations of refraction (or dispersion) in terms of the locations of colors, it became difficult to detect any relations between the noncontinuous changes of color location and the continuous variations of absorption, which were described as increases or decreases of the coefficient of absorption. Kundt's crossed prisms however exhibited the variations of refraction in terms of geometrical displacements. In this way, the variations of refraction could be measured continuously, and described as increases or decreases of the index of refraction. The crossed prisms thus vividly showed that the variations in the index of refraction were accompanied by corresponding variations in the coefficient of absorption, and the concomitant relations between these two continuous parameters immediately became self-evident.

3.4 Vibratory models and the theoretical unification

Just one year after Kundt's discovery, John Rayleigh proposed a qualitative account to explain the concomitant relations in terms of the interactions between the ether and the molecules of the medium. Rayleigh (1872, pp.321-323) used a mechanical analogy to illustrate the interactions between the ether and the molecules. The analogous model contained a pendulum suspended from a body subject to horizontal vibration. The motion of the pendulum was bound to interfere with the motion of the body, but how the vibration of the pendulum would affect the oscillation of the body depended upon the relations between the frequencies of the two vibrations. If the frequency of the pendulum was higher than that of the body, the motion of the pendulum would increase the virtual inertia of the body and its frequency. But if the frequency of the pendulum was lower than that of the body, the motion of the pendulum would diminish the virtual inertia and the frequency of the body. Now suppose that the ether was analogous to the suspending body and the molecules to the pendulum. Since absorption was the consequence of the resonance between the ether and the molecular vibrations, the position of the absorption band would indicate the frequency of the molecular vibrations. Below the absorption band (closer to the red end) the ether vibrated with a frequency lower than that of the molecules; consequently, the motion of the molecules increased the frequency of the ether and then the index of refraction. On the other side of the absorption band, the effect of the molecular oscillations was opposite. Because the frequency of the molecules were lower than that of the ether, the motion of the molecules diminished the frequency of the ether and the index of refraction.

Rayleigh’s qualitative account represented a significant breakthrough on the theoretical front. Unlike Cauchy who appealed to a stationary model, Rayleigh relied upon a dynamic model in which both the molecules of the medium and the ether were in vibration. It seems that, around 1872, the optical community had reached a consensus that some kind of vibratory model was the key to account for anomalous dispersion and its close connections with selective absorption. A couple quantitative explanations appeared in this year, all of which appealed to the interactions between ether vibrations and molecular oscillations. In 1872, for example, Meyer (1872) developed an account of anomalous dispersion by assuming that the ether experienced a resistance originating from the oscillating molecules of the medium. In the same year, Sellmeier offered an explanation of anomalous dispersion based solely upon energy considerations. Sellmeier (1872) assumed that, if light passed through the medium with a frequency identical to the one of the medium, the molecules would resonate and energy would be absorbed. After displacing the material particle, an ether wave lost a certain amount of energy, which explained the abnormal change of the refractive index. Both Meyer and Sellmeier were able to deduce formulas that captured the key feature of anomalous dispersion, that is, the indices of refraction would change abnormally in the areas near absorption bands.

However, neither Meyer’s nor Sellmeier’s formulas could be supported by the available experimental data, and they implied that the indices of refraction would become infinite within an absorption band. These problems were solved in 1875 when Helmholtz developed a more sophisticated mechanical model. Helmholtz (1875) believed that analyzing energy alone was not enough; an analysis of force was necessary since absorption involved the transformation of ether energy into the motion of molecules. He then reasoned that the molecules of the medium, under the impact of the ether waves, were subject to two other forces emanating from the surrounding molecules: a harmonic force of restitution and a frictional force of resistance. When the molecules absorbed energy from the ether waves, optical energy would be converted into thermal motion by the fictional force, and the loss of optical energy in turn would affect the velocity of the ether waves. Using two connected equations to represent the motions of both the ether waves and the molecules, Helmholtz deduced a formula that connected the index of refraction and the coefficient of absorption. At this point, dispersion and selective absorption were finally unified on the basis of a mechanical theory.

Helmholtz's theory of dispersion and selective absorption was purely mechanical. More sophisticated treatments of dispersion and selective absorption on the basis of electromagnetic theory appeared in the 1880s and 1890s. These electromagnetic accounts of dispersion and selective absorption were able to cover every feature revealed by experiments and to explain the two phenomena consistently. Although these electromagnetic accounts appealed to an essentially different kind of physical model, they still shared the same structure as Helmholtz's. Many physicists in the 1880s admitted that the basic principles of Helmholtz's model, including the assumption of the interactions between two vibratory systems and that of the harmonic and resistance forces, could be translated into the language of the electromagnetic theory at once (Glazebrook 1885, p.256). Thus, the theoretical unification of dispersion and selective absorption was first achieved by Helmholtz on the basis of a mechanical model, although today's textbooks usually attribute the success to the electromagnetic theory.

4. Conclusion

4.1 Instrumental obstacles and the failures in the 1830s

Powell's formula for dispersion and Tovey's formula for selective absorption provided impressive explanations of the phenomena on the basis of Cauchy's molecular ether theory, and could have unified these separate phenomena. Today Powell's formula is still cited in textbooks as a good approximation. Tovey's formula, though less known than Powell's, also captured the key feature of selective absorption. But the optical community of the time did not recognize and accept them as a successful unification.

Evidently, these early unification attempts failed because of several instrumental hurdles. As it has been explained in the previous section, the difficulties in obtaining high-quality gratings constituted an obstacle that hindered the replication of Fraunhofer's diffraction experiment, which was necessary for resolving the conflict between Powell and Brewster. In fact, in combination with the impact of other instruments, the problem of gratings was so deep that the replication of Fraunhofer's experiment became impossible. When Brewster conducted his diffraction experiments, he used a long rectangular aperture instead of a narrow slit to regulate the incident light. This new apparatus generated diffraction spectra substantially different from Fraunhofer's, and Brewster accordingly shifted his attention to the newly found oblique dark lines. When he requested a new grating to study these oblique lines, he did not follow Fraunhofer to ask for an increase of the density of the openings; instead, he asked for a reduction of the distance between openings. This was a new standard of gratings. To Brewster, Fraunhofer's gratings no longer represented the ideal apparatus for diffraction experiments. Thus, even if Brewster had obtained the grating he wanted, he would not have produced the same kind of diffraction spectrum as Fraunhofer's. Whether Brewster could obtain Fraunhofer's fine gratings was no longer the key for the replication. With a different experimental setup and a new standard of gratings, it became impossible for Brewster to replicate Fraunhofer's diffraction experiment.

Instruments were also responsible for the irreconcilable dispute between Powell and Brewster. Powell's opinion of the relations between prismatic and diffraction spectra and his method of taking the mean were deeply shaped by his instruments. On the one hand, his theodolite enabled him to make angular measurements; on the other hand, this instrument also limited him by affecting how he interpreted his measurements. Equipped with the theodolite, Powell naturally focused on angular parameters, such as angles of incidence, refraction, and diffraction. He consequently attributed the discrepancies between prismatic and diffraction spectra mainly to the difference in their angular sizes, which was an optical effect caused by instruments and had nothing to do with the nature of light. Thus, taking the mean was a logical solution in index determination when handling unmatched measurements. Brewster, however, conducted his studies with a different instrument and had a different understanding of the relations between prismatic and diffraction spectra. He did not use a theodolite; the key apparatus in his experiments on prismatic spectra was a powerful telescope. Without a theodolite, Brewster did not obtain any angular measurements, but the telescope enabled him to see a large number of spectral lines. The discovery of more than two thousand spectral lines in the prismatic spectrum renewed Brewster's interest in examining the chemical origins of spectra. Consequently, he interpreted the differences between prismatic and diffraction spectra in terms of the interactions between light and matter. According to Brewster, there was no reason whatsoever to group spectral lines with different chemical origins, and the method of taking the mean was completely unfounded and mistaken.

4.2 Instrumental unification and the success in the 1870s

The discovery of anomalous dispersion was a key to the success of unifying dispersion and selective absorption in the 1870s, because it directly contradicted the old Cauchy ether model and eventually triggered a series of pursuits in searching for new theoretical accounts of the phenomena. Obviously, anomalous dispersion was not found in a natural environment; instead, it only became observable in controlled experiments, with the help of carefully designed instruments. Talbot first generated this phenomenon by using crystallized prisms, but the optical community did not accept his discovery as a genuine optical phenomenon. Many, like Brewster, suspected that the phenomenon was merely an artifact or an illusion caused by defects of the instrument or the experimental design. The phenomenon of anomalous dispersion needed to be replicated and verified, but Talbot's crystallized prisms could not satisfy these demands. Thus, searching for an instrument that could stabilize the phenomenon of anomalous dispersion became critical, and hollow prisms, first introduced by Christiansen in 1870 and then adopted quickly by others, represented a breakthrough. By holding liquid in a sturdy vessel, hollow prisms could generalize stable anomalous dispersion. Furthermore, the simplicity of the instrument made it accessible and the verification of the phenomenon possible. Within a few months after Christiansen announced his discovery, many physicists replicated and confirmed the existence of anomalous dispersion. Only at this point was anomalous dispersion accepted by the optical community as a genuine physical phenomenon. Thus, instruments played a crucial role in generating and verifying the physical evidence that cleared away the theoretical obstacle to unification.

The role of instruments in our historical case was not limited to providing empirical evidence for testing theoretical models. It is very important to note that an instrumental unification of dispersion and selective absorption on the basis of Kundt's cross prisms had occurred prior to the theoretical unification. Kundt's apparatus clearly demonstrated that there were concomitant relations between the index of refraction and the coefficient of absorption. More important, Kundt's apparatus showed that the correlation between dispersion and selective absorption was neither coincident nor spurious, because it could be replicated in different experimental settings (filling the hollow prism with different absorptive substances) and because it could be measured in terms of precise parameters (the index of refraction and the coefficient of absorption). In this way, the apparatus of cross prisms made it improbable to attribute the correlation between dispersion and selective absorption to chance, and thus unified the two hitherto separate phenomena in the sense that it revealed the existence of causal relations behind them. In hindsight, this instrumental unification was even more significant than the theoretical unification achieved later.

The epistemological significance of theoretical unification consists in the fact that, when diverse phenomena (strictly speaking, descriptions of diverse phenomena) are unified by a theory, they provide the theory with better support. With a unifying theory, we can assert that our comprehension of the universe is improved as the number of independently acceptable assumptions is reduced. Or, in other words, we can say that we now understand the world better through fitting descriptions of various phenomena into a comprehensive system. However, comprehensive patterns, models, or theories used as the foundation of theoretical unification may not be justified empirically. This was exactly the situation in our historical case. Like the unification of optics and electromagnetism, the mechanical model that unified dispersion and selective absorption in the 1870s was never justified empirically, and it was quickly replaced by various electromagnetic models. Since the unification was achieved on the ground of an unjustifiable model or theory, it became questionable whether our understanding of the world had actually been improved.

However, reducing the number of independently acceptable assumptions or fitting descriptions of various phenomena into a comprehensive theory is not the only way to improve our understanding of the world. Our understanding of the world can also be improved through knowing how things work. A different but equally important pattern of explanation, as many philosophers of science suggest, consists in exhibiting an event-to-be-explained as occupying its place in a discernible pattern that is constituted by natural regularities in the form of causal relations. Thus, to explain an event is to identify the cause and to exhibit the causal processes or interactions between the cause and the event-to-be-explained.[17] This was exactly what Kundt's crossed prisms had achieved. By attributing the correlation between two hitherto separate phenomena to the existence of causal connections, Kundt's apparatus located the phenomena in a pattern of natural regularities and thus improved our understanding of the subject matter. In retrospect, the discovery of the concomitant relations between the index of dispersion and the coefficient of absorption, and the recognition of causal connections behind the correlation were far more important than the mechanical model that had never been verified. Because of these achievements, no one today would deny the significance of the historical efforts of unifying dispersion and selective absorption, although the unification did not produce an acceptable theoretical model.[18]

The moral drawn from our study is that the unification of dispersion and selective absorption in 19th century optics had its material and operational aspects. This finding coincides with many recent historical studies that find progress in science occurs at many levels other than the articulated level of scientific theory. Underneath the level of theory, the development of such elements as

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[17] This is the so-called ontic conception of scientific explanation, in opposition to the epistemic conception which defines explanations as arguments on the basis of the relations of logical necessity between explanans-statements and explanandum-statements; see Salmon (1984, pp.84-123).

[18] With a similar reason, no one today would deny the significance of the unification of electromagnetism and optics. Long before the theoretical unification exemplified by Maxwell's work, electromagnetic and optical phenomena had been unified instrumentally by Faraday, who demonstrated that magnets could cause the rotation of the plane of polarized light (the Faraday effect). Thus, although Maxwell's theoretical unification was built upon an unjustified physical model, his unification attempt still represented an important step in recognizing and understanding the physical connections between two hitherto separate phenomena.

instrumentation and skill were frequently crucial in determining the pace of scientific change.[19] In our historical case, many of the salient issues in the unification remained below the surface of optical theory, hidden beneath the explicit points regarding physical models or explanatory abilities. Thus, to fully understand the meaning of unification, in particular the unification of dispersion and absorption in the 1870s, it is necessary to go beyond the process of theoretical unification that hovers around physical models or explanatory power. More important, we need a new historiographical perspective that more highly appreciates the roles of instrumentation.

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[19] For example, Galison recently shows that the history of microphysics consisted of three quasi-autonomous levels: theory, experimentation and instrumentation. Each of these levels carried their own periodization, and the local continuities were intercalated, that is, no abrupt changes of theory, experimentation, and instrumentation occurred simultaneously (Galison 1997).

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