0039-3681(94)E0016-2

Artisanal Knowledge and Experimental Natural Philosophers:

The British Response to Joseph Fraunhofer and the Bavarian Usurpation of Their Optical Empire

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THE IMPORTANCE of skills and practices in the replication of scientific knowledge has been a central topic of interest in the history, sociology and philosophy of science over recent years. Some thirty years ago, philosophical studies by Mary Hesse, Paul Feyerabend, Thomas Kuhn and Norwood R. Hanson and historical studies by Gerald Holton began the assault against the doctrine of empiricism, which exclusively investigated the importance of verification and justification in replicating 'scientific discoveries'.[1] More recent studies by sociologists of science have contributed to empiricism's demise by introducing to science studies the notions of the 'skill-ladenness' and 'practice-ladenness' of the scientific enterprise.[2] There have also been numerous studies in the history and sociology of science which have undermined empiricism by showing how

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Received 25 *May* 1993; *in revised form* 19 *February* 1994.

[1]These scholars, quite famously, have argued that empiricism is not valid since there is no theory-independent language of observation. For example: M. Hesse, *Models and Analogies in Science* (London: Sheed & Ward, 1963); P. Feyerabend, 'Explanation, Reduction and Empiricism', in H. Feigl and G. Maxwell (eds), *Scientific Explanation, Space, and Time* (Minneapolis: University of Minnesota Press, 1962), pp. 28–97; T. Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1962); H. R. Hanson, *Patterns of Discovery: An Inquiry into the Conceptual Foundations of Science* (Cambridge: Cambridge University Press, 1971); and G. Holton, *The Scientific Imagination* (Cambridge: Cambridge University Press, 1978), see ch. 2.

[2]D. Gooding, 'Empiricism in Practice: Teleology, Economy, and Observation in Faraday's Physics', *Isis* **73** (1982), 46–67, and T. Pinch, 'Towards an Analysis of Scientific Observation: The Externality and Evidential Significance of Observational Reports in Physics', *Social Studies of Science* **15** (1985), 3–36, see p. 14.

Pergamon

Stud. Hist. Phil. Sci., Vol. 25, No. 4, pp. 549–575, 1994.

0039–3681/94 $7.00+0.00

successful replication is predicated upon the transmission and acquisition of material culture.[3]

Because much of the work of sociologists of science has been concentrated in the twentieth century, they have often been guilty of accepting *prima facie* that the established structure of science and its relationship with a broader society have always been as they find them now. In this essay, I wish to historicize the sociologists' notion of skills and practices, which, after all, are historically located and change over time. Since this essay deals with early nineteenth-century Britain and Bavaria, a critical insight into skills and practices as a cultural phenomenon can be gained. Precisely because this period witnessed rapid changes simultaneously in both society and the notion of skill, this essay takes neither society nor the scientific enterprise for granted.

As will be discussed below, John Herschel, David Brewster and Michael Faraday were all concerned with the skills and practices involved in the formation of a scientific discipline and how those skills and practices were manifested, and by whom, in society. The attitudes of these experimental natural philosophers toward artisanal skills and practices had ramifications not only for the newly emerging science of physics, but for the newly emerging plans of reform for Britain as well. These skills and practices became a central issue in two major debates of the 1820s and 1830s which form the political context of this essay: mechanization and educational reform. It turns out that these attitudes, which were not idiosyncratic but reflected a wider spectrum of political belief during this period, tell the historian how both society and the discipline of physics were constructed in pre-Victorian Britain.

Throughout the eighteenth century, Britain had been the undisputed leader in glass manufacturing and optical technology. But by the second decade of the nineteenth century, Britain's lead was usurped by Joseph Fraunhofer and his Optical Institute of Bavaria. The first portion of this essay analyses how Fraunhofer co-ordinated various resources at his disposal in order to produce the world's finest achromatic lenses. The formation of an optical community

[3]For example, M. Polanyi, *The Tacit Dimension* (New York: Anchor Press, 1967); M. Polanyi, *Personal Knowledge* (London: Routledge & Kegan Paul, 1958); M. Polanyi, 'The Republic of Science, Its Political and Economic Theory', *Minerva* **1** (1962), 54–73; H. M. Collins, *Changing Order: Replication and Induction in Scientific Practice* (Chicago: University of Chicago Press, 1992), pp. 51–78; S. Shapin and S. Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life* (Princeton: Princeton University Press, 1989), pp. 55–60; B. Latour, 'Give Me a Laboratory and I Will Raise the World', in K. D. Knorr-Cetina and M. Mulkay (eds), *Science Observed: Perspectives on the Social Study of Science* (London: Sage Press, 1983), pp. 141–170; C. Lawrence, 'Incommunicable Knowledge: Science, Technology and the Clinical Art in Britain 1850–1914', *Journal of Contemporary History* **20** (1985), 503–520; B. Latour, '*Post*modern? No, Simply *A*modern! Towards an Anthropology of Science', *Studies in History and Philosophy of Science* **21** (1990), 145–171, see p. 155; H. M. Collins, *Artificial Experts: Social Knowledge and Intelligent Machines* (Cambridge, Mass.: MIT Press, 1990); and W. Anderson, 'The Reasoning of the Strongest: The Polemics of Skill and Science in Medical Diagnosis', *Social Studies of Science* **22** (1992), 653–684, see pp. 675–678.

around Fraunhofer, the importance of the *Handwerkerkultur* to Bavaria, as well as Bavaria's much less hierarchical scientific culture, helped fuel the Institute's success.

The importance of the glass industry to the disciplines of optics and experimental natural philosophy in Britain is discussed in the second part of this essay. The excise tax, Napoleon's blockade of Great Britain from continental Europe, the decline in the social status of instrument makers in early nineteenth-century Britain, and the physical and social separation between opticians and makers of ordinary glass all contributed to the downfall of British optics and the futility of their attempts to recapture the lead.

The third part of this essay discusses how Fraunhofer's work became the standard for the calibration of achromatic lenses and how the British reacted to the usurpation of their optical hegemony. The responses of Herschel, Brewster and Faraday raise several intriguing issues relevant to the sociology and philosophy of science: whether artisanal skills can be replicated by a totally different scientific culture, how artisanal knowledge is communicated, and whether there is a purely philosophical reasoning which can produce artifacts such as achromatic lenses.

The paper as a whole illustrates how the boundaries of economics and science, which are often taken for granted, were, during this period, very blurred. Fraunhofer's artisanal skills, combined with an aggressive, reform-minded Bavarian government, gave rise to an optical technology which was to become the envy of the world. Freiherr Maximilian von Montgelas's governmental reforms backed by Prince Maximilian Joseph IV (after 1 January 1806, King Maximilian I) were intended to raise Bavaria to the technological, scientific and economic levels of post-Revolutionary France. These reforms shifted the bureaucratic power from the clergy of the Roman Catholic Church to a new group of men, the *Beamten*, or civil servants. Britain, on the other hand, taxed its glass makers, while the Industrial Revolution lowered the social status of skilled artisans. The economic conditions of early nineteenth-century Britain inevitably led to that nation's downfall in optical technology.

In short, this paper analyses how two very different scientific cultures, one in Britain and one in Bavaria, attempted to achieve the same goal: the production of achromatic lenses. These two cultures had very different views of skilled labour and of what constituted necessary and sufficient knowledge for optical lens production. Some claimed that philosophical knowledge was necessary and sufficient for optical lens production. Others stated that artisanal practices were necessary and sufficient, and claimed that philosophical knowledge was simply insufficient. The various beliefs in the communicability of scientific knowledge were very local and culturally dependent. Hence, I shall refer to them as cultural epistemologies.

1. Fraunhofer's Enterprise[4]

Fraunhofer's optical research on the dark lines of the spectrum was a fusion of four distinct, yet related, zones:[5] the bureaucratic, the scientific/technological, the monastic and the artisanal. The bureaucratic zone was created, in part, to fulfil Napoleon's request for a map of his new ally, Bavaria. The resulting scientific/technological zone, the Mathematico-mechanical Institute, provided optical and surveying instruments for the ordnance surveying project to construct Napoleon's map. The Secularization of Bavarian monasteries and cloisters in 1803, which gave rise to the monastic zone, generated the laboratory space and part of the skilled labour to assist Fraunhofer. Finally, the importance of the *Handwerker* in general, and Fraunhofer in particular, to early nineteenth-century Bavaria represented the artisanal zone.

At the request of Napoleon, Prince Maximilian Joseph IV ordered the ordnance surveying of Bavaria in 1801 when France became allies with Bavaria after the French defeat of Austria at Hohenlinden on 3 December 1800.[6] This enterprise was directed by the French military officers Henry, Bonné and Moreau of the Bureau Topographique and incorporated Bavarian and French military surveyors and engineers.

The year 1802 witnessed the establishment of the Mathematisch-mechanisches Institut by Joseph Liebherr and Georg Reichenbach, the latter having returned from Britain after a study tour of instrument making.[7] This institute specialized in the production of astronomical and ordnance surveying instruments for the Bureau Topographique. Colonel Henry advised Reichenbach on improvements to the borda circle, a surveying instrument invented by Le Noir towards the end of the eighteenth century, used for the determination of angles between triangles for the triangulation of areas. Henry stayed with the project for two years until being replaced by Ulrich Schiegg, a Benedictine monk, mathematician and astronomer.[8]

After the Secularization of Bavarian monasteries and cloisters, Schiegg had time to devote to the project. He became the head astronomer of the ordnance surveying enterprise and concentrated his effort on the angle calculations for triangulations. Reichenbach incorporated Schiegg's recommendations into

[4]The following section is a summary from M. W. Jackson, 'Die britische Antwort auf Fraunhofer und die deutsche Hegemonie der Optik', *Deutsches Museum Jahruch* 1992 (Munich: Deutsches Museum, 1993), pp. 116–136, and M. W. Jackson, 'Illuminating the Opacity of Glass Making: Joseph von Fraunhofer's Use of Monastic Culture and Architecture in Achromatic Lens Production', in P. Galison (ed.), *The Architecture of Science* (forthcoming).

[5]For the notion of trading zones, see P. Galison, *Image and Logic: The Material Culture of Modern Physics* (Chicago: University of Chicago Press, forthcoming), ch. 9, 'The Trading Zone: Coordinating Action and Belief'.

[6]J. J. Sheehan, *German History* 1770–1866 (Oxford: Clarendon Press, 1989), pp. 235–236.

[7]W. von Dyck, *Georg von Reichenbach* (Munich: Deutsches Museum, 1912), pp. 18–19.

[8]*Ibid.*, p. 19 and p. 23.

Ramsden's original design of theodolite in order to produce the world's most precise surveying instrument. The Bureau Topographique (after 1808, when the French left Bavaria to occupy newly acquired portions of Prussia, the enterprise was called Das Topographische Bureau) ordered its theodolites exclusively from Reichenbach and Liebherr's Mathematisch-mechanisches Institut. Theodolites measure angles which, in conjunction with the measurement of a base line and simple trigonometric equations, were used for the determination of land distances based on the 'fixed' positions of stars.

Two Bavarians played crucial roles in the ordnance surveying project. Joseph Niggl was the head optician of the enterprise, while Joseph Utzschneider, entrepreneur, financial advisor and former Privy Councillor, was the official in charge of the operations. Utzschneider became joint partner of the Mathematisch-mechanisches Institut with Reichenbach and Liebherr on 20 August 1804 and later became in charge of managing the Optisches Institut, a portion of the Mathematisch-mechanisches Institut. All of the aforementioned Bavarians play a major role in my account of Fraunhofer. As Utzschneider's now famous account reveals, the young Fraunhofer miraculously survived the collapse of his *Meister's* house. Prince Maximilian Joseph IV was so inspired by the child that he appointed Utzschneider to see to his care. After a disappointing new apprenticeship, Fraunhofer was doomed to live the life of a working-class orphan. Utzschneider intervened and appointed Schiegg to instruct the boy in physics and mathematics. In 1806 Utzschneider gave the promising young optician a position in the newly formed Optisches Institut.[9] Niggl taught Fraunhofer the art of optical lens production.

As a result of Napoleon's blockade of Great Britain from continental Europe in 1806, British lenses disappeared from the European market. The Mathematisch-mechanisches Institut relied on British glass for their optical instruments. Fraunhofer was instructed to assist Pierre Louis Guinand, the Swiss bell and clock maker from Les Brenets, in the production of achromatic lenses. Guinand taught him how to manufacture bubble- and striae-free glass. Fraunhofer learned quickly: too quickly in fact. He soon began to manage the glass production, accusing Guinand of producing inferior glass. Highly insulted, Guinand returned to Switzerland in December of 1813. From that point on, Fraunhofer was the sole director of the Optisches Institut.

The former cloister was purchased by Utzschneider in 1805 from the Bavarian government after the Secularization of 1803. The governmental

[9] J. von Utzschneider, *Kurzer Umriß der Lebens-Geschichte des Herrn Dr Joseph von Fraunhofer, königlich bayerischen Professors und Akademikers, Ritters des königlichen bayerischen Civil-Verdienst, und des königlich dänischen Danneborg-Ordens, Mitgliedes mehrerer gelehrten Gesellschaften, etc.* (Munich: Rösl'schen Schriften, 1826), pp. 8–10.

organized Secularization usurped the riches and property of the monasteries, convents and cloisters. The cloister in Benediktbeuern was perfectly located. It was situated in a large forest which provided the wood for the fuel of the glass ovens, and a quartz quarry, which provided the ingredients for the glass, was only 10 km away. More importantly, Fraunhofer drew upon the skills of monks as well as labourers in the vicinity who had previously assisted in the production of achromatic lenses for the monastery before the Secularization. The Benedictine monks had a thousand-year tradition of glass making.[10] The monks also possessed the necessary knowledge of optics.

It was in this particular context that Fraunhofer performed his now famous six lamp experiment which revealed the dark lines in the solar spectrum, the so-called Fraunhofer lines. In this experiment, described in his 'Bestimmung des Brechungs- und Farbenzerstreuungs-Vermögens verschiedener Glasarten in Bezug auf die Vervollkommnung achromatischer Fernröhre'[11] Fraunhofer took advantage of the huge space provided him by the former monastery. He employed six lamps as the source of light (Fig. 1). Light from each lamp travelled through a slit in a screen placed in front of the lamps and converged on to a prism thirteen feet (*bayerischer Fuß*) away.[12] This prism, called the *Zuordnungsprisma*, was made from crown glass and had an angle of approximately 40°. The light refracted by that prism was then channelled through yet another screen with a slit. The refracted light travelled 692 feet[13] to another prism, whose refractive and dispersive indices were to be determined. Such a distance was necessary to guarantee that the incidental rays would be as parallel as possible. This prism was mounted on a modified theodolite, an instrument normally used by surveyors to determine the angles formed by the incidental with the refracted rays of light. Once obtained, Fraunhofer used a simple trigonometric relationship, similar

[10]For the most comprehensive account of the skilled labour of monks in glass making see: F. Lerner, *Geschichte des deutschen Glaserhandwerks*, 2nd edn (Schondorf: Hofman, 1981); E. Vopelius, *Entwicklungsgeschichte der Glasindustrie Bayerns bis* 1806 (Stuttgart: J. G. Cotta'schen Buchhandlung, 1895); R. Haller, *Historische Glashütten in den Bodenmaiser Wäldern: Ein Beitrag zur Geschichte des Glases im Bayerischen Wald* (Grafenau: Morsak, 1975); P. Friedl, *Glasmachergeschichten und Glashüttensagen aus dem Bayerischen Wald und dem Böhmerwald* (Grafenau: Morsak, 1973); L. Lobmeyr, *Die Glasindustrie, ihre Geschichte, gegenwärtige Entwicklung und Statistik* (Stuttgart: W. Spemann, 1874); J. Blau, *Die Glasmacher in Böhmer- und Bayernwald in Volkskunde und Kulturgeschichte*, 2 vols (Regensburg: Michale Lassleben Kallmünz, 1954 and 1956).

[11]*Joseph von Fraunhofer's Gesammelte Schriften: Im Auftrage der Mathematisch-Physikalischen Classe der königlichen bayerischen Akademie der Wissenschaften*, ed. E. Lommel (Munich: Verlag der königlichen Akademie in Commission bei G. Franz, 1888), pp. 3–31: originally appeared in *Denkschriften der Königlichen Akademie der Wissenschaften zu München für die Jahre* 1814 *u.* 1815 **5** (1817).

[12]This experiment is also summarized in F. A. J. L. James, 'The Discovery of Line Spectra', *Ambix* **32** (1985), 53–70, see pp. 54–58.

[13]It is important to note here that because Fraunhofer's 'laboratory' was a large monastery, such a distance was possible.

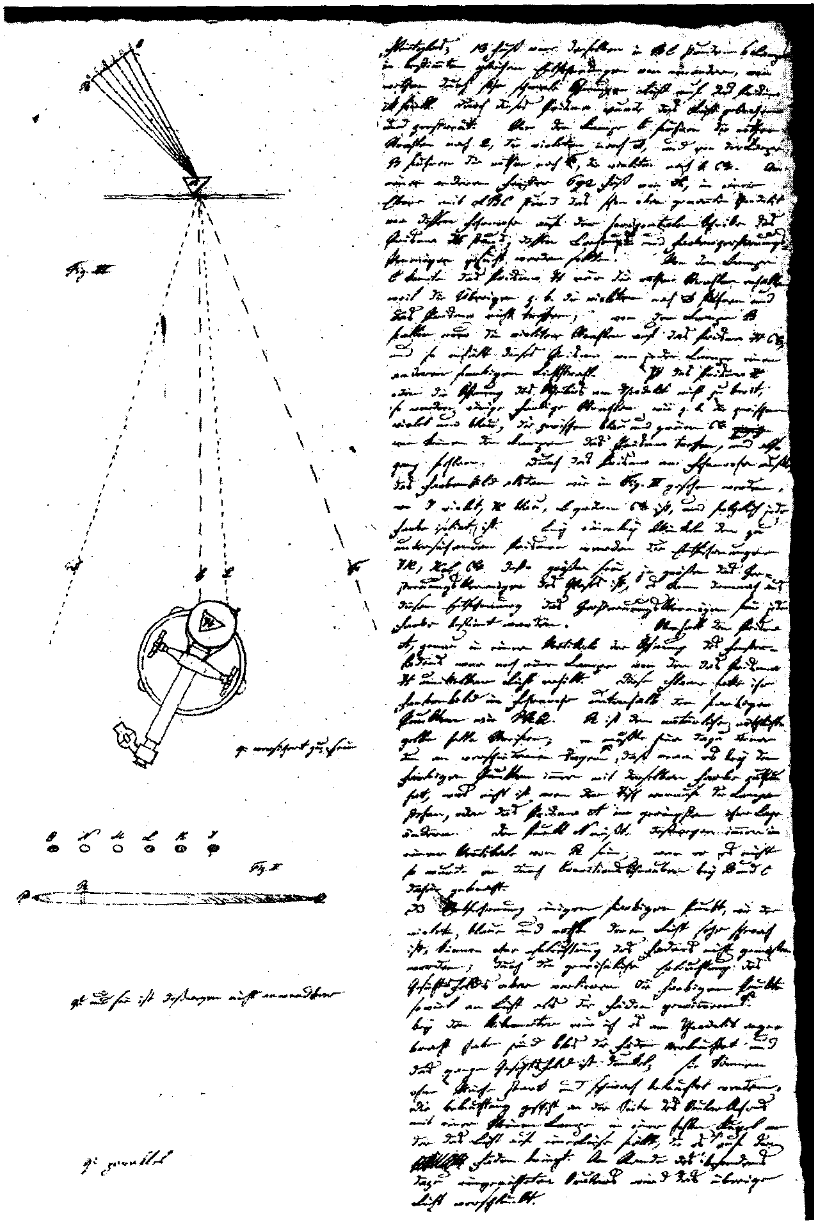

Fig. 1. A page from Fraunhofer's manuscript 'Bestimmung des Brechungs- und Farbenzerstreuungs-vermögens verschiedener Glasarten'. The original is found in the Deutsches Museum, Munich, Photo No. 33018. Reprinted with their kind permission.

to the one used by Boscovich,[14] to determine the refractive indices of the varying colours.

n = refractive index
r = the angle of the refracted ray
s = the angle of the incidental ray
y = the angle of the prism

$$n=\sqrt{(\sin r+\cos y\cdot\sin s)^2+(\sin y\cdot\sin s)^2}/\sin y.$$

Fraunhofer's contribution to the technique was the use of the dark lines in the spectrum to demarcate the spectral colours. In doing so, one could obtain the refractive index for a much smaller portion of the spectrum, thereby creating a much more precise calculation. Fraunhofer observed a fairly thick line in the reddish-yellow portion of the spectrum.[15] He concluded that the light emitted from fire always possessed this streak. When he used sunlight as his light source in a variation of the aforementioned experiment, he was amazed to see hundreds (574 to be exact) of dark lines across the spectrum.[16] He proceeded to use these lines as boundaries:

> As the lines of the spectrum are seen with every substance of uniform density, I have employed these lines for determining the index of refraction of any substance *for each coloured ray* [my emphasis]. This could be done with greater exactness, since most of the lines are very distinct and well marked. For these experiments, I chose the largest lines, because with substances of low refractive power, or with prisms of small refracting angles, the minute lines could scarcely be perceived even with strong magnification.[17]

These lines provided his modified theodolite with natural cross-hatchings. Fraunhofer could label minute sections of the spectrum and use the lines demarcating the sections as points where precise refractive indices could be ascertained. This was precisely the technology which the British lacked. They did not have a calibrating standard for the refractive indices of each colour. After Herschel's visit to Benediktbeuern, and the English translation of this

[14] R. J. Boscovich, *Dissertationes Quinque ad Dioptricum* (Vindobonae: Johannis Thomae, 1767), p. 142. Note that the equation Fraunhofer used is equal to Boscovich's formula when $M=1$: $m^2=(\sin y+M\cos b\sin a)^2+M^2(\sin a)^2(\sin b)^2/(\sin b)^2$. Fraunhofer could have been familiar with this equation from the textbook he used: G. S. Klügel, *Analytische Dioptrik in zwey Theilen: Der erste enthällt die allgemeine Theorie der optischen Werkzeuge: der zweyte die besondere Theorie und vortheilhafteste Einrichtung aller Gattungen von Fernröhren, Spiegelteleskopen, und Mikroskopen* (Leipzig: Johann Friedrich Junius, 1778). It would be unwise, however, to speculate about the equation's origin. The key point is that it is a simple trigonometric relation typical of sets of problems found in Klügel's text, as well as others at the time.

[15] Subsequent research in spectroscopy showed that this line was actually two lines very close together.

[16] Fraunhofer, *Gesammelte Schriften, op. cit.*, note 11, p. 12. Fraunhofer placed his modified theodolite in a darkened room with a narrow vertical aperture in a window shutter. Sunlight fell upon a prism of flint glass placed in front of the telescope attached to the theodolite. The theodolite was 24 feet from the window, and the angle of the prisms was approximately 60°.

[17] *Ibid.*, p. 14.

paper in 1823 and 1824, the British adopted Fraunhofer's procedure for achromatic lens calculation. Bavaria's reform-oriented government combined the needs of the Bureau Topographique with the intellectual and manual resources of the monks and the manual resources of skilled artisans. Fraunhofer co-ordinated these diverse enterprises, or zones, in solving the problem of achromaticity.

2. Britain's Glass Industry

Bavaria's rise to optical fame was concurrent with a drastic deterioration in the British glass industry, the decline of the status of the skilled artisan, and the existence of a labour hierarchy which impeded fertile exchange of information between ordinary glass makers and opticians. By the early 1820s, Britain had lost its lead in both glass production and optical technology. Napoleon's blockade of Britain, the occupation and subsequent ordnance surveying of Bavaria, and the rise of an optical community centred around Fraunhofer, all contributed to Britain's downfall. Interestingly, as Bennett has shown, the early nineteenth century witnessed a steady decline in the social status of instrument makers in Britain.[18] Manual labour became a pejorative term tainted by its working-class connotations. The fall in the social status of instrument makers and opticians reflected a much more encompassing debasement of skilled artisans in Britain. The glass-making profession followed excessively the division of labour created by the Industrial Revolution.[19] Technical innovation and the abundance of cheap labour threatened the skilled artisans' existence. An allegiance between the aristocracy and bourgeoisie was fused in order to deprive the working class of its political rights.[20] The power of the state was used—or rather, abused—in an attempt to destroy the trade unions.[21]

Concurrent with the decline of the instrument makers in England came the decline of the glass factories. By 1833 the number of glass houses in London had diminished to three.[22] The major reason for the rapid decline in Britain in general, and in London in particular, was the very harsh excise tax levied on glass makers by the government from the inception of the Excise Act of 1746 until its repeal in 1845. During those one hundred years, the tax had been

[18] J. A. Bennett, 'Instrument Makers and the "Decline of Science in England": the Effects of Institutional Change on the Elite Instrument Makers of the Early Nineteenth Century', in P. R. DeClercq (ed.), *Nineteeth-Century Scientific Instruments and Their Makers* (Amsterdam, 1985), pp. 13–27.

[19] E. P. Thompson, *On the Making of the English Working Class* (New York: Random House, 1963), p. 261.

[20] J. Morrell and A. Thackray, *Gentlemen of Science: Early Years of the British Association for the Advancement of Science* (Oxford: Clarendon Press, 1981), p. 10.

[21] Thompson, *op. cit.*, note 19, p. 269.

[22] H. J. Powell, *Glass-Making in England* (Cambridge: Cambridge University Press, 1923), pp. 156–157.

increased in 1777 and throughout the 1780s.[23] It greatly decreased the amount of glass produced in England.

In 1812 an additional duty was imposed upon glass manufacturers by the Chancellor of the Exchequer which resulted in the decrease in glass production by more than one third throughout the kingdom between 1812 and 1832.[24] Continental production of glass, particularly in France and the German states, also contributed to the decline in British glass production. An account of 1832 conveyed a blunt message to the government: 'Could any facts more forcibly point out the pernicious tendency of heavy duties upon articles of domestic manufacture, or more clearly indicate the course which it were wise to follow in remodelling to as great an extent and as quickly as is practicable, this branch of our financial system?'[25]

The passage concluded with a rather strong admonition to the government explaining the ramifications of their short-sighted policy:

> It is principally owing to these restrictions that so much foreign glass is now brought into this country in the face of what may be considered an amply protecting duty. . . . Nor is this restriction only commercially wrong, since it forms a matter of just complaint on the part of chemists, that they are unable to procure utensils fitted for effecting many of the nicer operations connected with their science, because the due protection of the revenue is thought to require that such utensils shall be formed out of that quality of glass alone which, apart from all considerations of price, is otherwise, from its properties, really unfitted for the purpose. . . . The manufacturer, and the interests of science are, consequently, made to suffer.[26]

This excise tax was rather brutally enforced by governmental officers. Two to three officers were actually quartered in every glass works. They were responsible for registering the total weight of molten glass and for preventing the removal of any unweighed glass from the premises.[27] When the officers suspected wrong-doing, they would often fit large locks on the entrance doors of annealing kilns and lears. Later, this became standard practice. The officers would fit these locks, at the expense of the glass manufacturer, every Friday or Saturday, and the doors would remain locked until Monday morning. They were also in charge of supervising any machine repairs which were often necessary in glass manufacturing. If an officer was absent when a glass pot broke, the entire glass house was shut down. More daring manufacturers would convince their learmen to make the reparations without the officer being informed. If they were caught, the plant would incur large excise penalties. The

[23] R. Dodsworth, *Glass and Glassmaking* (Aylesbury: Shire Publications, 1987), p. 13.
[24] G. R. Porter, 'A Treatise on the Origin, Progressive Improvement and Present State of the Manufacture of Porcelain and Glass', *The Cabinet Cyclopaedia* (London: Longman, Rees, Orme, Browne and Green and John Taylor, 1832), p. 141.
[25] *Ibid.*, pp. 142–143.
[26] *Ibid.*, p. 143.
[27] Powell, *op. cit.*, note 22, p. 153.

most annoying practice was the officers' surveillance of the melting pots. The addition of the smallest piece of metal into the pots without the officers' knowledge and consent was penalized by a £50 fine.[28]

A glass manufacturer gave as evidence the following report to the Commissioners of Excise in 1833:

> Our business and premises are placed under the arbitrary control of a class of men to whose will and caprice it is most irksome to have to submit and this under a system of regulations most ungraciously inquisitorial. We cannot enter into parts of our own premises without their permission; we can do no one single act in the conduct of our own business without having previously notified our intention to the officers placed over us. We have in the course of the week's operations to serve some 60 to 70 notices on these, our masters, and this under heavy penalties of about £200 to £500 for every neglect.[29]

The Commission came to the conclusion that the regulation threatened British research in 'the most important branches of Science' as well as hindering British competition in the glass trade.[30]

It was to take another twelve years before the government repealed the excise tax. This tax required the glass manufacturer to pay for each glass house (approximately £20 in 1826) as well as for a licence to produce glass. He also needed to pay a fee *pro rata* for the weight of the melted glass in the pots, as well as a payment proportional to the excess in weight of manufactured glass over 40% (and later 50%) of the determined weight of molten glass.[31]

As a result of the excise duty regulations, the glass industry was divided into five sections: flint, crown, plate, broad and bottle.[32] Only flint and crown glass were subject to the tax. Since stringent regulations were enforced by excise officers, glass factories specialized either in glass which was taxed or in glass which was free from the duty. Interestingly, different regions of England specialized in different types of glass production. Stourbridge and Birmingham (and the Midlands in general) were renowned for their flint glass. Broad glass was manufactured in the North, particularly Newcastle and St Helens, while crown glass was produced in Stourbridge and bottle glass in Yorkshire.[33] This partitioning, as I shall discuss below, hindered Britain's attempt to recapture the optical lead as there was no co-ordination of skilled practices among the differing enterprises. The division of labour was so extreme that, as an article in the *Flint Glass Maker's Magazine* claimed, 'the Crown Glass Maker, the German Sheet Blower, and the Bottle Maker are all confined to one article each

[28] A. Pellatt, *Curiosities of Glass Making: With Details of the Processes and Productions of Ancient and Modern Ornamental Glass Manufacture* (London: David Bogue, 1849), pp. 67–68.

[29] As quoted in Powell, *op. cit.*, note 22, p. 153.

[30] *Ibid.*, p. 154.

[31] As quoted in *ibid.*, p. 155.

[32] Takao Matsumura, *The Labour Aristocracy Revisited: The Victorian Flint Glass Makers* (Manchester: Manchester University Press, 1983), p. 13.

[33] *Ibid.*, pp. 14–15.

and all of them are the same thing over again, there is no variety: everyday's work is but a repetition of the former[,] stays always the same[,] no changing of patterns'.[34] It should also be stressed that since British glass houses were located in large, industrial cities, they, unlike their Bavarian counterparts, came under the influence of trade unions which continued to separate differing labour practices. Since there was no deforestation law in Bavaria until 1883, glass houses remained in forests where wood was plentiful, far removed from the trade unions of large Bavarian cities, such as Nuremberg, Augsberg and Munich.

There was a hierarchy among the different type of glass makers, with the flint glass makers at the top, followed by crown glass makers, flat glass makers and bottle makers. The *Flint Glass Maker's Magazine* proudly proclaimed in 1858:

> The members of our society may count themselves among those who have the honour of contributing daily to the luxuries of the tables of the nobility of the land, including Her Majesty the Queen. Seeing, then, that we labour at a beautiful art, is it not only our duty and privilege to excel with the same—to be ambitious for our own credit and attainments, and to study taste, richness and beauty?[35]

Flint glass makers would not condescend to the making of glass consumed by the working class. They did not wish 'their beautiful trade of glass-making [to] be brought as low as nail making'.[36] The term 'flint' actually came to denote the aristocratic portion of a particular industry, such as the 'flint tailors', in order to contrast that labour with the less skilled labour of the 'dung tailors'.[37] The British government wished to render a luxury commodity more expensive, thereby restricting its availability to the upper bourgeoisie and aristocracy. Those few flint glass makers who were patronised extensively by the Crown or by the upper bourgeoisie supported the tax, to the dismay of their less fortunate colleagues.

The excise duty not only crippled the glass manufacturers, it also greatly hindered opticians' attempts to perfect achromatic lenses. Pellatt, reflecting upon the 1810s and 1820s, claimed in 1849 that 'neither plate Glass nor bottle Glass manufacturers were subject to the surveillance of the pots: this made it exclusively injurious to the flint glass maker, and was almost a prohibition of alteration of flint, or experiments, and consequent improvements'.[38] Flint glass was of prime importance to the production of achromatic lenses. Because of the presence of lead oxide, it has the crucial property of refracting light through greater angles than crown glass. John Dollond had complained that it was

[34]As quoted in *ibid.*, p. 19. Although this comment was made in 1851, it certainly described the labour practices involved in glass making decades earlier. E. P. Thompson has shown that the use of the word 'aristocracy' to describe the highly skilled aspects of certain forms of labour appeared well before 1850 (he cites examples from the 1820s and 1830s); *op. cit.*, note 19, pp. 236–237.

[35]As quoted in Matsumura, *op. cit.*, note 32, p. 23.

[36]As quoted in *ibid.*

[37]Thompson, *op. cit.*, note 19, p. 253, pp. 255–256.

[38]Pellatt, *op. cit.*, note 28, p. 68. Note that 'Pellatt' is often spelled 'Pellat'.

simply impossible to experiment with flint glass for the construction of a perfectly achromatic telescope due to the excise.[39] The crown glass, the other glass crucial for the manufacturing of achromatic lenses which Dollond used in his experiments, also came under the charge of the excise officer at the Spon Lane works of Chance Brothers. An excise law required that all crown glass must be less than one ninth of an inch in thickness, which was too thin for Dollond's research.[40] Indeed, the fact that the excise duty hindered optical research was evident from the fact that the government removed the restrictions occasioned by the excise laws and regulations on glass experiments performed by Faraday and other members of the Royal Society subcommittee.[41]

3. British Response to the Bavarian Threat

Fraunhofer's calibration technique of using the dark lines of the spectrum for determining refractive indices became the standard for optical lens production. In 1825, Brewster wrote that it was to Fraunhofer's essay on the six lamp experiment that one must turn for the 'most accurate knowledge' in achromatic lens calibration.[42] An anonymous article in *The Edinburgh Journal of Science* defined an excellent prism as one which could clearly produce many Fraunhofer lines.[43] This was a change from the eighteenth-century definition of a superior prism: one which produced the Newtonian spectrum.

In his 1831 work entitled *A Treatise on Optics*, Brewster was explaining Newton's analysis of the colours of the spectrum. He confessed that 'no lines are seen across the spectrum . . ., and it is extremely difficult for the sharpest eye to point out the boundary of the different colours' while replicating Newton's *experimentum crucis*.[44] He then diagrammatically compared the lengths of the colours of the spectrum as experimentally determined by Newton with Fraunhofer's results obtained by using his and Guinand's flint glass[45] (Fig. 2).[2] The old standard-bearer had been replaced by a new, foreign one. Later in the treatise he lamented that

> the neglect into which this important branch of our national manufactures was allowed to fall by the ignorance and supineness of the British government, stimulated foreigners to rival us in the manufacture of achromatic telescopes. M. Guinand of

[39]As quoted in R. W. Douglas and S. Frank, *A History of Glassmaking* (Henley-on-Thames: G. T. Foulis, 1972), p. 32.

[40]*Ibid.*

[41]M. Faraday, 'On the Manufacture of Glass for Optical Purposes', *Philosophical Transactions of the Royal Society of London* **120** (1830), 1–57, here p. 2.

[42]*Edinburgh Journal of Science* **2** (1825), 344–348, see p. 348.

[43]'Remarks on Dr Goring's Observation on the Use of Monochromatic Light with the Microscope', *Edinburgh Journal of Science* **5** (1831), 153–158, see p. 154.

[44]D. Brewster, *A Treatise on Optics* (London: Longman, Rees, Orme, Brown and Green and John Taylor, 1831), p. 67.

[45]*Ibid.*, pp. 67–68.

lengths of the colours to be as follows, in the kind of glass of which his prism was made. We have added the results obtained by Fraunhofer with flint glass.

	Newton.	Fraunhofer.
Red - -	45	56
Orange - -	27	27
Yellow - -	40	27
Green - -	60	46
Blue - -	60	48
Indigo - -	48	47
Violet - -	80	109
Total length	360	360

These colours are not equally brilliant. At the lower end, L, of the spectrum the red is comparatively faint, but grows brighter as it approaches the orange. The light increases gradually to the middle of the yellow space, where it is brightest; and from this it gradually declines to the upper or violet end, K, of the spectrum, where it is extremely faint.

(64.) From the phenomena which we have now described, sir Isaac Newton concluded that the beam of white light, S, is compounded of light of seven different colours, and that for each of these different kinds of light the glass, of which his prism was made, had different indices of refraction; the index of refraction for the *red* light being the least, and that of the violet the greatest.

If the prism is made of *crown glass*, for example, the indices of refraction for the different coloured rays will be as follows: —

	Index of Refraction.		Index of Refraction.
Red - - -	1·5258	Blue - - -	1·5360
Orange - -	1·5268	Indigo - -	1·5417
Yellow - -	1·5296	Violet - - -	1·5466
Green - - -	1·5330		

If we now draw the prism, B A C, on a great scale, and determine the progress of the refracted rays, supposed to be incident upon the same point of the first surface C A, by using for each ray the index of refraction in the pre-

Fig. 2. A page from David Brewster's Treatise on Optics *comparing a Newtonian flint-glass prism with one produced by Fraunhofer. Reproduced with the kind permission of the Whipple Library, Department of the History and Philosophy of Science, University of Cambridge.*

> Brenetz, in Switzerland, and M. Fraunhofer, of Munich, successively devoted their minds to the subject of making large lenses of flint glass, and both of them succeeded.[46]

Fraunhofer created a new product in which the optical experiments built in had already reached closure, unlike their Newtonian counterparts. Newtonian prisms were not of a sufficient quality to generate the dark lines in the spectrum. Hence, one could only obtain the refractive index of the glass sample by taking the arithmetic average of the refractive rays at the edge of the red and violet colours.

The British response to Bavarians' ever-extending lead was the creation of a Joint Royal Society and Board of Longitude Committee for the Manufacturing of Glass for Optical Purposes on 1 April 1824.[47] It was the explicit goal of this Joint Committee to produce glass which could rival Fraunhofer's.[48] Members included such luminaries as Humphrey Davy, Thomas Young, John Herschel and William Wollaston.[49] At the 5 May 1825 meeting of the Joint Committee, it was decided that Herschel, George Dollond and Faraday form a subcommittee for the purpose of superintending the glass research.[50]

It turns out that the Fraunhofer enterprise, although a very intriguing story in itself, can be used as a point of comparison of cultural epistemologies—not only between Bavarian *Naturwissenschaftler* and British experimental natural philosophers, but also between leading figures of the British scientific intelligentsia themselves. This section compares and contrasts the attitudes of Brewster, Herschel and Faraday to the 'practical, communicable knowledge' of skilled artisans.

a. David Brewster

Fraunhofer's work was not published in English until 1823–1824 when his aforementioned 'Bestimmung des Brechungs- und Farbenzerstreuungs-Vermögens verschiedener Glasarten' of 1817 was translated by Brewster and published in two parts (vols 9 and 10) in *The Edinburgh Philosophical Journal.* During 1822 and 1823 Brewster was attempting to solve the problem of

[46] *Ibid.*, p. 359.

[47] Royal Greenwich Observatory Archives 14/8, folio 17–20. F. A. J. L. James has argued that the Royal Society subcommittee was created to bail out the financially doomed Board of Longitude. See his 'Time, Tide and Michael Faraday', *History Today* (1991), 22–34, see pp. 30–31, and his 'The Military Context of Chemistry: The Case of Michael Faraday', *Bulletin of the History of Chemistry* **11** (1991), 36–40, see pp. 37–38. I shall take another line, as the reader will see. I think that both James's point and mine need to be considered as joint reasons for the subcommittee's creation. They certainly are not mutually exclusive.

[48] Royal Society Committee Minutes Book (henceforth RS CMB) 1, 127 and Royal Society Domestic Manuscripts (RS DM) vol. 3, folio 26 and RS DM vol. 3, folio 22.

[49] RS CMB. 1, 96.

[50] RS CMB. 1, 102.

chromatic aberration in microscopes by using monochromatic lamps.[51] Hence, Fraunhofer's technique of using the spectral dark lines as a more precise system of calibration for determining the refractive indices aroused Brewster's interest. But it is noteworthy that six years had elapsed before this English translation.[52] Fraunhofer's paper was translated into French in *Schumacher's astronomische Abhandlungen* in 1823 as well. The English publication of Fraunhofer's paper generated a massive response to his work in British periodicals. Subsequent articles of Fraunhofer were published in *The Philosophical Magazine and Journal*, *The Edinburgh Philosophical Journal* and *The Edinburgh Journal of Science*. More importantly for the historian, many dates involving the English interest in glass production begin to fall into place.

In 1825 Brewster wrote a brief report on Fraunhofer's achromatic refractor which the Russian government had ordered for their Dorpat observatory. We are told that 'Frauenhofer [sic] is said to have succeeded beyond his most sanguine expectations'.[53] Also, in that same issue, Brewster provided a description of this telescope. He began by stating, that

> By means of this [Guinand's] glass, M. Fraunhofer, the director of the Optical Institute or Manufactory at Benedictbauern [sic], near Munich, has constructed achromatic telescopes far superior to any that have hitherto been made; and we can assure our readers, of what many of them will deem incredible, that this eminent artist can now make acromatic object glasses with an aperture of *eighteen inches*. But it is not merely in the optical part of the instrument that M. Fraunhofer has been successful. His various improvements on the apparatus which accompanies the telescope, and his ingenious micrometers for measuring angles of all kinds in the heavens, have received the sanction of some of the most eminent practical astronomers in Europe, and are now considered as constituting an instrument of incalculable value for general astronomical observations.[54]

In the next year Brewster published Struve's description of Fraunhofer's masterpiece. He then attached his comments to the report's conclusion.

> Such is the description of Fraunhofer's telescope given by Professor Struve; and we think that no Englishman can read it without feelings of the most poignant regret, that *England has now lost her supremacy in the manufacture of achromatic telescopes*, and the government one of the sources of its revenue. In a few years she will also lose her superiority in the manufacture of the great divided instruments for fixed observatories. When these sources of occupation for the scientific talent decline, the scientific character of the country must fall along with them, and the British government will deplore, when it is too late, her total inattention to the scientific establishments of the empire. When a great nation ceases to triumph in

[51] David Brewster, 'Description of a Monochromatic Lamp for Microscopial Purposes, &c. with Remarks on the Absorption of the Prismatic Rays by Coloured Media', *Transactions of the Royal Society of Edinburgh* **9** (1823), 433–444. See also James, *op. cit.*, note 12, pp. 59–60.

[52] Recall that this paper was published in 1817. See note 11 above.

[53] *Edinburgh Journal of Science* **2** (1825), 174.

[54] *Ibid.*, pp. 305–306 (italics in the original).

her arts, it is no unreasonable apprehension, that she may cease also to triumph by her arms.[55]

In Fraunhofer's eulogy published in 1827, Brewster translated several sections of Utzschneider's biography of Fraunhofer published a year earlier.[56] Once again, Brewster used the conclusion of the article to launch a diatribe against His Majesty's government. Brewster argued that Bavaria rewarded instrument makers while Britain ignored them. Brewster was well aware how seriously the Bavarians took the *Handwerkerkultur*.

> His [Fraunhofer's] own sovereign Maximilian Joseph was his earliest and his latest patron, and by the liberality with which he conferred civil honours and pecuniary rewards on Joseph Fraunhofer, he has immortalized his own name, and added a new lustre to the Bavarian crown. In thus noticing the honours which a grateful sovereign had conferred on the distinguished improver of the achromatic telescope, it is impossible to subdue the mortifying recollection, that no wreath of British gratitude has yet adorned the *inventor* of that noble instrument. England may well blush when she hears the name of Dollond pronounced without any appendage of honour, and without any association of gratitude. . . . The pre-eminence which England had so long enjoyed in the manufacture of the achromatic telescope [is now] transferred to a foreign country. . . . The British minister who shall first establish a system of effectual patronage for our arts and sciences, and who shall deliver them from the fatal incubus of our patent laws, will be regarded as the Colbert of his age, and will secure to himself a more glorious renown than he could ever obtain from the highest achievements in legislation or in politics.[57]

Fraunhofer's success and the British failure provided Brewster with a perfect resource with which to attack the English government, particularly its Tory establishment, and the Royal Society of London. Brewster, after all, had labelled the Royal Society 'an incubus pressing with its livid weight' on science.[58] His use of the Fraunhofer episode fits squarely into the 'decline of science in England' debate, mounted by him and Charles Babbage in the 1820s and 1830s.[59] Indeed, Babbage mentions Fraunhofer's use of the dark lines in his *Reflections on the Decline of Science in England* of 1831.

Brewster was always sympathetic to artisans. This is evidenced by his support of artisans when they protested the publishing of their trade secrets. In 1821 Brewster collaborated with Leonard Horner in the creation of the Edinburgh School of Arts for the scientific education of local (i.e. Scottish) artisans and mechanics.[60] In that same year Brewster urged the establishment of a Scottish

[55]*Ibid.*, **5** (1826), p. 110 (italics in the original).
[56]Utzschneider, *op. cit.*, note 9.
[57]*Edinburgh Journal of Science* **7** (1827), 1–11, see pp. 10–11.
[58]*Edinburgh Review* **60** (1835), 392.
[59]Morrell and Thackray, *op. cit.*, note 20.
[60]S. Shapin, 'Brewster and the Edinburgh Career in Science', in A. D. Morrison-Low and J. R. R. Christie (eds), *'Martyr of Science:' Sir David Brewster* 1781–1868 (Edinburgh: Royal Scottish Museum, 1984), pp. 17–23, see p. 20.

Society of Arts in an attempt to promote and reward Scottish inventions.[61] He did not believe that technical, manual skills could be taught in the same manner as the rational principles of geometry. Skilled labour instruction necessitated specialized schools, such as the Edinburgh School of Arts, which British educational reforms ignored. He fought to impede the replacement of skilled labourers by machinery. He also held a nationalistic vision of the scientific enterprise.[62] This is seen by his intense desire to establish the British Association for the Advancement of Science. This Association was to be modelled upon the Gesellschaft Deutscher Naturforscher und Ärzte.[63] Brewster hoped that this would spark British royal patronage of the sciences to match German patronage schemes.

Brewster certainly did not subscribe to the view that skills are universal. Indeed, he never thought the British attempt to produce Fraunhoferian lenses would succeed: 'We ourselves predicted sixteen years ago, that the committee [of the Royal Society and Board of Longitude] neither would nor could accomplish the object for which they were associated, and we can now record the melancholy truth, that the experimental glass house has been long closed, and the experimenters have disappeared'.[64] Once again Brewster attacked the British government for taxing the glass industry. He continued to emphasize the *practical* knowledge of Guinand in creating achromatic lenses:

> But though we have thus lost the monopoly of the achromatic telescope, and are now obliged to import the instrument from rival states, there is nevertheless a law of progress in *practical* [my emphasis] science, with which neither ignorant governments, nor slumbering institutions, nor individual torpor can interfere. What a conclave of English legislators and *philosophers* [my emphasis] attempted in vain, was accomplished by a humble peasant [Guinand] in the gorges of the Jura, where no patron encouraged, and no exciseman disturbed him.[65]

In 1832, after Faraday discontinued his work on optical glass, Brewster wrote: 'I presume you [Faraday] have met with some little difficulties of a *practical* [my emphasis] kind in the formation of large lenses'.[66] Brewster proclaimed that Fraunhofer 'united the highest scientific attainments with great mechanical and practical knowledge'.[67] According to Brewster, Fraunhofer improved upon Guinand's work by possessing 'a thorough knowledge of chemistry and physics

[61] *Ibid.*

[62] *Ibid.*, p. 21.

[63] Morrell and Thackray, *op. cit.*, note 20, p. 44.

[64] D. Brewster, 'The Earl of Rosse's Reflecting Telescope', *North British Review* **2** (1844–1845), 175–212, see p. 190.

[65] *Ibid.*, pp. 190–191.

[66] Brewster to Faraday, 8 August 1832, in *The Correspondence of Michael Faraday*, vol. 2, ed. Frank A. J. L. James (London: Institution of Electrical Engineers, forthcoming). Original in the Archives of the Institution of Electrical Engineers, MS EC 2. I would like to thank Frank A. J. L. James for providing me with a copy of this letter.

[67] Brewster, *op. cit.*, note 64, p. 192.

. . . and [inventing] the theory of manipulation, of which Guinand knew only the results'.[68]

Brewster claimed that there was not an explicit, philosophical procedure for making glass, but rather a skilled, manual procedure discovered and perfected by the Bavarian *Handwerker*, Fraunhofer. His solution to the British glass crisis was to appeal to the canniness of Scottish artisans, particularly Robert Blair.

While Faraday and the subcommittee busied themselves with finding alternatives to Bavarian flint glass, Brewster recalled Scottish technologies for producing achromatic telescopes, reporting his alternative technology in *The Edinburgh Journal of Science* in 1826: 'it has often struck us with surprise, that no attempt has been made to introduce and to improve the *achromatic telescopes with fluid object-glasses*, invented and actually constructed by our countryman Dr Blair'.[69] Liquid lenses can overcome chromatic aberration because the fluid in the lens refracts the variously coloured rays of the spectrum in the same proportion as crown glass. By 1827 it was known that sulfurates of carbon could provide a perfect correction of the chromatic aberration, dispersing the coloured rays through the same angle as crown glass did.[70]

Brewster's attitude stood in sharp contrast to Herschel's sentiment towards artisanal knowledge. Brewster's emphasis on the locality of skilled labour, his skeptical attitude toward the role of the philosopher in attempting to emulate the practices and products of the skilled artisan, his support of specialized schools for artisans and his attempts to thwart the substitution of skilled labourers by machinery, were much in line with Scottish Whig, anti-establishment, anti-Tory, anti-Royal Society and anti-England politics.

b. John Herschel

The differences between British and Bavarian glass-making traditions became most pronounced when Herschel attempted to gather information from Fraunhofer on achromatic lens production in order to inform the Joint Committee. In Benediktbeuern, the two traditions, and cultures, met *vis à vis*. During September of 1824, John Herschel travelled to the Continent where he met up with Fraunhofer on 19 September.[71] Herschel, upon being greeted in the former cloister wrote to Babbage: 'I saw Frauenhofer [sic] & all his works *but* the one most desireable to see: his glass-house, which he keeps enveloped in thick darkness'.[72] As von Rohr has argued, Fraunhofer would not sell raw glass

[68] *Ibid.*

[69] *Edinburgh Journal of Science* 4 (1826), 283 (italics in the original).

[70] Archibald Blair, 'On the Permanency of Achromatic Telescopes Constructed with Fluid Object-Glasses', *Edinburgh Journal of Science* 7 (1827), 336–342.

[71] Herschel's diary entries relevant to Fraunhofer are reprinted in M. von Rohr, 'Eine Erinnerung an Joseph Fraunhofer', *Forschungen zur Geschichte der Optik* 1 (1928), 2–6.

[72] Herschel to Babbage, 3 October 1824, Royal Society of London Archives. Herschel Letters HS.2.199.

from his glass house for reasons of secrecy.[73] Fraunhofer also would not permit Herschel to witness the labour practices involved in glass manufacturing. Because the Optical Institute was a profit-seeking business, strict measures were taken to differentiate between public and private knowledge. Fraunhofer was caught between conflicting interests. On the one hand, he wished to ensure his Institute's hegemony of achromatic lens production. Since a portion of his salary was based on merchandise sold, he obviously had a vested interest in keeping the recipe and skilled labour practices involved in lens manufacturing a secret. On the other hand, Fraunhofer wished to be accepted by the scientific community. Therefore, he needed to render certain portions of his enterprise public. He both published and demonstrated the method for determining the refractive indices of the colours for different specimens of glass, but never revealed the procedure for procuring those specimens.[74] Thus, Fraunhofer's glass-making techniques were not communicated to Herschel. Fraunhofer, from considerations of secrecy, reckoned that witnessing the labour practices would give potential competitors too much insight. As we are told by a letter from Herschel,[75] Fraunhofer demonstrated how one could produce the dark lines in the spectrum and how those lines could be used as a system of calibration for achromatic lenses. Critically, he revealed nothing else.

Herschel did not despair that Fraunhofer would neither show him the skilled labour involved nor the pieces of glass in different stages of the processes, only the finished products, for which he wholeheartedly thanked Fraunhofer.[76] Henry Fox Talbot provided Herschel with lenses from the Optical Institute after Fraunhofer's death in 1826. Herschel received other samples from the Optical Institute a year later. He wrote to Faraday on 27 August 1827: 'I have just got some prisms from Utzschneider's manufactory among which is a large one of flint glass of the utmost perfection being like a piece of solidified water without a trace of a vein or imperfection of any kind. This shews [sic] . . . that the problem is capable of being resolved'.[77] This sentiment reflects the belief that Fraunhofer's superior prisms could be replicated by the British Joint Committee without any knowledge of Bavarian skilled labour practices of optical glass production. Herschel, being the archetypal representative from

[73]von Rohr, *op. cit.*, note 71, p. 3.

[74]For the notion of public versus private knowledge, see for example Shapin and Schaffer, *op. cit.*, note 3, pp. 69–72.

[75]Reprinted in A. Seitz, *Joseph Fraunhofer und sein Optisches Institut* (Berlin: Verlag von Julius Springer, 1926), pp. 111–112. We are also told that Herschel witnessed Fraunhofer's demonstration of the dark lines of the spectrum by Charles Babbage in his *Reflections on the Decline of Science in England, and on Some of its Causes* (London: B. Fellowes, 1830), pp. 210–211. See also *Edinburgh Journal of Science* **2** (1825), 344–348.

[76]Fraunhofer gave Henry Fox Talbot a glass prism, who passed it on to Herschel in London in 1825. Deutsches Museum Urkunden- und Handschriften-Sammlung N 14/20, 5389.

[77]Letter 332 Herschel to Faraday, Royal Institution Manuscripts F3 B397. Reprinted in *The Correspondence of Michael Faraday*, vol. 1 (1811–December 1831, Letters 1–524), ed. F. A. J. L. James (London: Institution of Electrical Engineers, 1991), p. 438.

regal Britain, attempted to replicate what Fraunhofer was accomplishing in terms of his own scientific culture, hence concepts such as communicability of skills and practical knowledge were part of the British response to Fraunhofer but were not present in Fraunhofer's work itself. Herschel asserted that skills could be communicated by the artifacts themselves.

Herschel's trip to Benediktbeuern and his cultural epistemology of artisanal knowledge must also be put in its proper context. He was, of course, the leader of scientific reform in Britain in the 1820s and 1830s, and was the most powerful man in British scientific circles from the late 1820s onwards. Philosophical reasoning, experimental science and economic science were, in Herschel's eyes, all interrelated. Having been a Senior Wrangler at the University of Cambridge, it followed that he would insist that knowledge was indeed communicable. After all, that was precisely what a Senior Wrangler did: communicate complex, technical knowledge.

After his meeting with Fraunhofer in September of 1824, Herschel praised Fraunhofer's theoretical technology[78] of using the dark lines in the spectrum as a method of calibrating lenses.[79] We are told of Herschel's replication of the Fraunhofer lines in Babbage's *Reflections on the Decline of Science in England*:

> A striking illustration of the fact that an object is frequently not seen, *from not knowing how to see it*, rather than from any defect in the organ of vision, occurred to me some years since, when on a visit at Slough. Conversing with Mr Herschel on the dark lines seen in the solar spectrum by Fraunhofer, he inquired whether I had seen them; and on my replying in the negative, and expressing a desire to see them, he mentioned the extreme difficulty he had had, even with Fraunhofer's description in his hand and the long time which it had cost him in detecting them. My friend then added, 'I will prepare the apparatus, and put you in such a position that they shall be visible, and yet you shall look for them and not find them: after which, while you remain in the same position, I will instruct you *how to see them*, and you shall see them, and not merely wonder [why] you did not see them before, but you shall find it impossible to look at the spectrum without seeing them'.
>
> On looking as I was directed, notwithstanding the previous warning, I did *not* see them; and after some time I inquired how they might be seen, when the prediction of Mr Herschel was completely fulfilled.[80]

This passage is quite remarkable. Quite clearly, tacit knowledge acquired by personal witnessing was required in order to see the phenomenon.[81] The ability to replicate the experiment required Herschel to travel to Benediktbeuern.

[78]For the notion of theoretical technology, see Andrew Warwick's pioneering paper: 'Cambridge Mathematics and Cavendish Physics: Cunningham, Campbell and Einstein's Relativity 1905–1911', *Studies in History and Philosophy of Science* **23** (1992), 625–656 and **24** (1993), 1–25.

[79]Seitz, *op. cit.*, note 75, p. 112.

[80]Babbage, *op. cit.*, note 75, pp. 210–211 (italics in the original).

[81]This portion of my story is similar to Shapin and Schaffer's work on witnessing, *Leviathan and the Air-Pump, op. cit.*, note 3, pp. 55–60 as well as H. M. Collins' notion of tacit knowledge as depicted in his 'The TEA Set: Tacit Knowledge and Scientific Networks', *Science Studies* **4** (1974), 165–186.

Upon his return, he could replicate the phenomenon, but without multiplying the context of the monastery.[82] Britain's technology of optics was sophisticated enough to replicate the phenomenon by recreating only certain aspects of Fraunhofer's laboratory. The scientific cultures of Britain and Bavaria were very different, but the knowledge that each generated was certainly not incommensurable. Herschel, upon his return to England, was able to instruct others on 'how to see the lines'.[83]

Herschel used the glass crisis as a legitimation for his own agenda for reform of the Royal Society. But by 1827, he began to realize how difficult that would be. In December of 1827 he resigned from the post of Secretary of the Royal Society. After that date, his interest in the subcommittee's glass enterprise waned considerably.

More importantly, the Fraunhofer episode illustrates Herschel's attitude toward skilled artisans. Unlike Brewster, Herschel claimed that the production of lenses could be improved by philosophical knowledge. Opticians and instrument makers were to follow the cue of experimental natural philosophers, who in turn were to render their theories accessible to the manageable artisan. One can easily see how Brewster, who supported artisanal training in specialized schools and strongly opposed the spread of machinery, necessarily felt threatened by Herschel's antithetical stance. Herschel strongly upheld the notion of the universality, rather than an enculturated model, of skill. His *Preliminary Discourse on the Study of Natural Philosophy* published in 1830 reveals Herschel's belief in the universality of the scientific enterprise: 'It is not one of the least advantages of these pursuits [the study of natural science], . . . that they are altogether independent of external circumstances'.[84] He, unlike Brewster, stated that practical mechanics belonged to the domain of purely theoretical knowledge:

> Practical Mechanics is, in the most pre-eminent sense, *a scientific art*; and it may be truly asserted, that almost all the great combinations of modern mechanism, and many of its refinements and nicer improvements, are creations of pure intellect, grounding its exertion upon a moderate number of very elementary propositions in theoretical mechanics and geometry.[85]

He continued by asserting that 'the advantages [of practical mechanics] conferred by the augmentation of our physical resources through the medium of increased knowledge and improved art have this peculiar and remarkable

[82]Latour, *op. cit.*, note 3, pp. 141–170.

[83]The notion of someone needing to have a trained eye in order to visualize a phenomenon is very similar to Foucault's concept of the gaze. M. Foucault, *The Birth of the Clinic: An Archaeology of Medical Perception* (New York: Vintage Books, 1975), translated by A. M. S. Smith from the original: *Naissance de la clinique* (Paris: Presses Universitaires de France, 1963).

[84]J. F. W. Herschel, *Preliminary Discourse on the Study of Natural Philosophy* (London: Longman, Rees, Orme, Brown & Green and John Taylor, 1830), p. 15.

[85]*Ibid.*, p. 63 (italics in the original).

property—that they are in their nature diffusive, and cannot be enjoyed in any exclusive manner by a few'.[86]

Finally, Herschel criticized empirical art since it tended towards incommunicable knowledge. Science, by Herschel's definition, was communicable by two means: either via the experimental natural philosophers themselves or by their artifacts. Scientific art, unlike empirical art, made the technical mystery accessible to all cultures:

> They [the arts, such as practical mechanics] cannot be perfected till their whole processes are laid open, and their languages simplified and rendered universally intelligible. Art is the application of knowledge to a practical end. If the knowledge be merely accumulated through experience, the art is *empirical*; but if it be experience reasoned upon and brought under general principles, it assumes a higher character, and becomes a *scientific art*. . . . The whole tendency of empirical art, is to bury itself in technicalities, and to place its pride in particular short cuts and mysteries known only to adepts; to surprise and astonish by results, but conceal processes. The character of science is the direct contrary. It delights to lay itself open to enquiry; and is not satisfied with its conclusions, till it can make the road to them broad and beaten: and in its applications it preserves the same character; its whole aim being to strip away all technical mystery, to illuminate every dark recess, and to gain free access to all processes, with a view to improve them on rational principles. It would seem that a union of two qualities almost opposite to each other—a going forth of the thoughts in two directions, and a sudden transfer of ideas from a remote station in one to an equally distant one in the other—is required to start the first idea of *applying science*.[87]

Fraunhofer, according to Herschel, practised scientific art; after all, Herschel did award Fraunhofer with an associate membership to the Royal Astronomical Society of London in 1825.[88] Hence, he thought he could learn Fraunhofer's procedures during his visit in 1824. If that should fail, which it did, the work of Faraday should have been able to recover the procedures by 'reading them off' the final product. The transfer of technology from Benediktbeuern to London is precisely what Herschel meant by 'applying science'.

In an attack on Babbage and Brewster's call for a national scientific agenda, Herschel condemned a nationalist view as impeding the universal effectiveness of science. He added that the rise of new journals throughout Europe placed 'observers of all countries on the same level of perfect intimacy with each other's objects and methods'.[89] They 'serve to direct the course of general observation, as well as to hold out, in the most conspicuous manner, models for emulative innovation'.[90] Herschel believed that journals were sufficient for the replication of specific technologies. This claim that the replication of technical procedures could be achieved by reading the written word alone serves as a

[86] *Ibid.*, p. 68 (italics in the original).
[87] *Ibid.*, pp. 70–72.
[88] Deutsches Museum, Urkunden- und Handschriften Sammlung N 14/20, 5389.
[89] Herschel, *op. cit.*, note 84, p. 352.
[90] *Ibid.*

good example of Herschel's belief that technical, artisanal knowledge could be communicated without the personal witnessing of the labour involved in the production of that knowledge.[91]

In short, Herschel was attracted to Fraunhofer's work because of the precision measurements which the Bavarian's instruments produced. He noted in his *Preliminary Discourse* the importance of improved observation by means of instruments adapted for exact measurement: 'What an important influence may be exercised over the process of a single branch of science by the invention of a ready and convenient mode of executing a definite measurement . . .'.[92] The crucial difference between Herschel's and Brewster's cultural epistemologies is that Herschel claimed that the scientific enterprise could imitate the skilled labour of artisans by virtual witnessing or by being able to 'read off' the skills from a finished product.

Herschel's solution to Britain's dilemma was also quite different from Brewster's. Herschel stated that reflecting telescopes, and not refracting telescopes or telescopes with liquid lenses, were the answer to the problem of achromaticity. It was in the 1820s that he committed himself completely to astronomical reflectors, the instrument with which his father brought fame to England and a technology in which the British hegemony was never questioned.[93] His star catalogues of the 1820s and 1830s, and his famous *Cape Observations* of 1847 were a compilation of his observations through a reflecting telescope.

After Fraunhofer's construction of the Dorpat refractor, Struve became Herschel's main rival. Indeed, it was claimed that Fraunhofer's refractor was as good as a reflecting telescope with twice the aperture.[94] Fraunhofer himself even suggested that refractors were simply more precise instruments than reflecting telescopes. Herschel responded to Fraunhofer's claim with a terse reply defending his and his father's telescopes.[95] In the 1840s while reflecting upon the British telescope crisis, Lord Rosse of Ireland wrote: 'Many practical men to whom I have spoken seem to think that after Fraunhofer's discoveries, the refractor has entirely superseded the reflector, and that all attempts to improve the latter instrument are useless'.[96]

c. Michael Faraday

Being Britain's leading chemist during this period, Faraday, not surprisingly, attempted to replicate Fraunhoferian lenses by using chemistry. Faraday

[91]For the notion of virtual witnessing, see Shapin and Schaffer, *op. cit.*, note 3, pp. 60–65.

[92]Herschel, *op. cit.*, note 84, p. 354.

[93]H. C. King, *The History of the Telescope* (Cambridge, Mass.: Sky Publishing, 1955), pp. 120–143.

[94]*Ibid.*, p. 206.

[95]J. F. W. Herschel, 'Observations on Mr Fraunhofers' Memoir on the Inferiority of Reflecting Telescopes when Compared with Refractors', *Quarterly Journal of Science* **20** (1826), 288–293.

[96]King, *op. cit.*, note 93, p. 206.

originally shared Herschel's view of 'scientific art', and for nearly six years set out to replicate Fraunhofer's prisms and lenses. As time went on, however, Faraday began to realize that German flint glass was simply impossible to reproduce. 'But be it remembered that it is not a mere analysis, or even the developement [sic] of *philosophical* [my emphasis] reasoning that is required: it is the solution of difficulties, which, as is the case of Guinand and Fraunhofer, required many years of a *practical* [my emphasis] life to effect . . .'.[97] This quotation is from a paper which Faraday presented as a series of lectures at the Royal Society in November and December of 1829 and which was subsequently published in 1830 summarizing the results of his experiments on glass. This paper began as a tribute to Fraunhofer's and Guinand's practical knowledge:

> It must be well known to the scientific world, that these difficulties [of glass manufacturing for optical purposes] have induced some persons to labour hard and earnestly for years together, in hopes of surmounting them. Guinand was one of these: his means were small, but he deserves the more honour for his perseverance and his success. He commenced the investigation about the year 1784, and died engaged in it in the year 1823. Fraunhofer laboured hard at the solution of the same *practical* [my emphasis] problem. He was a man of profound science, and had all the advantages arising from extensive means and information, both in himself and others. He laboured in the glass-house, the work-shop, and the study, pursuing without deviation the great object he had in view, until science was deprived of him also by death. Both these men, according to the best evidence we can obtain, have produced and left some perfect glass in large pieces . . .[98]

Faraday continued by pointing out the possibility that 'the knowledge they acquired was altogether *practical* [my emphasis] and personal, a matter of minute experience, and *not of a nature to be communicated* [my emphasis] . . .'.[99] As Faraday's own manipulative skills proved to be insufficient, he began to realize that the knowledge of the labour-intense process of lens and prism production could not be obtained from the lenses and prisms themselves.

Faraday set about using his knowledge of chemistry to find alternative pathways to produce achromatic lenses. His solution was quite different from either Herschel's or Brewster's. He manufactured glass with silicated borates of lead which, similar to the lead oxide in Bavarian flint glass, determined the refractive index of the glass. Faraday's experiments explicitly compared the results of his glass with Guinand's specimens obtained by Talbot and given to Herschel. On 27 April 1826 Faraday reported to the Joint Committee that 'you will observe that the glass is not yet equal to Guignand's [sic] in density or in the proportion of oxide of lead . . .'.[100] By 1827 it became clear to Faraday that

[97] Faraday, *op. cit.*, note 41, p. 4.
[98] *Ibid.*, pp. 1–2.
[99] *Ibid.*, p. 2.
[100] Royal Society Domestic Manuscripts (RS DM) vol. 3, folio 26. See also RS DM vol. 3, folio 22.

the English could simply not produce flint glass as well as their Bavarian counterparts. Faraday's attempts at reverse engineering failed. One of the reasons for this was the excise tax on flint and crown glass in Britain. Faraday himself told W. H. Smyth that 'the best step to ensure improvement [of optical glass in Britain] will be to take off the Excise duty'.[101] Although Faraday's research was specially exempt from paying this duty, the tax had taken its toll. It still hampered British research on optical glass from the mid-eighteenth century until 1845. Guinand and Fraunhofer, in the meantime, had accumulated an insurmountable lead. Also, Faraday's lack of information on Bavarian optical lens production, coupled with the severing of common glass-making practices from optical glass practices in Britain, added to his and the subcommittee's frustrations.

4. Conclusion

This essay has discussed why supremacy in optical technology shifted from Britain to Bavaria during the third decade of the nineteenth century. But this is not simply a story of Bavarian success and British failure. The central theme of this essay has been Fraunhofer's artisanal knowledge and the responses to it by leading British experimental natural philosophers. The skills and labour of artisanal practices provide a heuristic tool for analysing how these philosophers formulated a new scientific discipline, physics, and a new reformed society. The 1820s was a crucial period in British history since it was precisely this period when Herschel, Babbage, Brewster and Faraday were busying themselves with defining the content of a new science within the framework of a new society. The role and nature of skill and practice in science and society are precisely what were at stake at the time.

Herschel certainly recognized the importance of artisans, particularly instrument makers. Yet he claimed that their skilled practices were not a part of the corpus of scientific knowledge; they only enabled the production of such knowledge. In Herschel's view, skill was subservient to science. It was up to experimental natural philosophers (such as himself) to formulate general rational, mathematical principles which could render the skilled practices of the artisans accessible to other experimental natural philosophers. Appropriately, he thought that rational mechanics should be taught at artisanal schools cropping up throughout Britain as a result of the educational reforms. He certainly did not claim that manual skills, such as lens-grinding, should be included in the curriculum. Babbage held a similar, if not harsher, view of artisanal knowledge *vis à vis* scientific knowledge. He never appreciated the skilled labour of the working class as evidenced by his stance in favour of mechanization at the cost of dismissing the workers.

[101]Reprinted in King, *op. cit.*, note 93, p. 189.

Brewster found himself on the other side of the scientific and political spectrum. He always emphasized the practical knowledge exhibited by skilled artisans which could not be mimicked by philosophical reasoning. Similarly, he wanted Scottish artisanal schools to include manual training in their curriculum. He was also a staunch opponent of mechanization. Skills and labour formed a major component of Brewster's views of both physics and society.

Faraday initially hoped that there was an explicit, philosophical method of reproducing artisanal labour, but after six years of experimentation was disappointed. He realized, quite controversially, that philosophers could not manage artisans. This essay has argued that different individuals have held different, and often antithetical stances, on the replication and communicability of artisanal knowledge, and that historical approaches can explain those views by analysing the organization and status of the labour of artisans.

Acknowledgements — I especially thank Andrew Warwick, also Lorraine Daston, Michael Dettelbach, Frank A. J. L. James, Peter Galison, Simon Schaffer, and the anonymous referees for their comments on earlier versions of this essay. The research culminating in this essay has been supported by a fellowship from the Mellon Foundation as well as by the National Science Foundation, Grant Number SBE-9223098.