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Chapter 1

Introduction: Making Light Count

On a cool Ides of March in 1858, a handful of people across central England stood outdoors and watched the sunlight fade. One peered at a newspaper; another carefully positioned a lit candle as he squinted at the sun; a third held up a thermometer. Near Oxford an enthusiast tried to cast shadows with an oil lamp, while in Northamptonshire another uncovered his last slip of photographic paper.

The inspiration behind these activities involving flames, newsprint, rulers, exposures and watery eyes was the Astronomer Royal, George Biddell Airy. In the previous month's number of the *Monthly Notices of the Royal Astronomical Society*, Airy had set out a programme to observe the forthcoming annular solar eclipse. Among other tasks, he urged his readers 'to obtain some notion or measure of the degree of darkness'. His suggestions included determining at what distance from the eye a book or paper, printed with type of different sizes, could be read during the eclipse, and holding up a lighted candle nearly between the sun and the eye to note at how many sun-breadths' distance from the sun the flame could be seen. Later in the article, under the heading 'meteorological observations', Airy advised that 'changes in the intensity of solar radiation be observed with the actinometer or the black-bulb thermometer'.[1]

The observers' submissions covered the range from qualitative to quantitative observations. One noted that the change in intensity during the eclipse was 'not greater than occasionally happens before a heavy storm'.[2] Another held a footrule to the glass of a lantern, and found that, before the eclipse, 'at 12 inches distance the sunlight was still so strong that the lantern cast no circle of light on the paper held parallel to the glass. It was, however, perceptible at a distance of 9 inches. Whilst my pencil, held before it, cast a shadow at no greater distance than an inch.' During the eclipse, on the other hand, 'the lantern cast a very perceptible light, and the shadow was made at a distance of 8 inches from the paper'.[3] This observer had responded to Airy's exhortation for intensity data, but had made no attempt to manipulate the numbers obtained. By contrast, using an extension of Airy's text-reading technique, C. Pritchard obtained a numerical estimate of the reduction in intensity during the eclipse. Cutting up 'a considerable number of exactly similar pieces. . . of the leading articles of the Times newspaper', he affixed them to a vertical screen. He then noted the distance at which he could distinctly read the type as the sunlight faded, recording the distance to a tenth of a foot. Assuming 'that the distinctness with which a given piece of writing may be read varies inversely as the square of the distance and directly as the illumination of the writing; then the amount of light lost at the greatest obscuration of the sun was 2/5ths that of the unobscured illumination'.

James Glaisher, one of Airy's assistants at the Greenwich Observatory, employed the actinic method.[4] This involved exposing photographic paper at regular intervals during the eclipse. He noted both the times required to produce 'a slight tinge' of the paper, and to colour the paper to 'a certain tint'. This method, producing a seemingly objective record on paper, nevertheless relied on human judgement regarding the equality of tint. The observer cautioned, though, that 'since fixing the photographic impressions, it should be borne in mind that the deeper tints have become lighter in the process, whilst the feebler portions marking the occurrences of the greatest phase remain unaltered'.[5] None of the observers had much time; the sun was behind the entire disc of the moon for scarcely 15 seconds.

Airy was a strong supporter of 'automated' and quantifiable methods in astronomy, to permit large-scale and reliable data collection. He looked to photography as one means to achieve that end.[6] Another was via quantitative instruments – devices that could yield a numerical value from an observation instead of a qualitative impression. The most observer-independent of the methods he proposed for the eclipse observations was measurement with the black-bulb thermometer. The temperature indicated by a blackened bulb thermometer, particularly 'when the bulb is inclosed in an exhausted glass sphere',[7] was related to the intensity of radiant heat (infrared radiation, in modern parlance) rather than to heat conduction from the ambient air. It was thus a direct measure of solar intensity. Glaisher and others monitored temperature to 0.1º F, but did not attempt to analyse their data to infer changes in intensity.

The records of the 1858 eclipse suggest the ambivence of these astronomical observers towards quantitative intensity data. There was no consensus about what methods were relevant, nor on what degree of 'quantification' was useful. Nowhere in Airy's article or his respondents' accounts was a clear <u>*purpose*</u> for intensity measurement expressed. The data were to be acquired for descriptive use rather than to test a mathematically expressed theory. As mentioned above, most observers failed even to reduce their data to an estimate of the change in intensity during the eclipse: Pritchard's '2/5ths' estimate was the only one from over two dozen reports. The observers did not use their results to determine the obscuration of the solar disk, for example, nor to infer the relative intensity of the solar corona to that of the body of the sun. Instead, the estimates of brightness filled out an account having more in common with natural historians' methods than those of physical scientists. Despite astronomy's long history of accurate angular, temporal and spatial measurement, there was little attempt by these mid-19th century observers to bring such standards to the measurement of light intensity . The observers supplied Airy's request by obtaining merely <u>*a notion*</u> instead of <u>*a measure*</u> of the degree of darkness.

The case of the 1858 eclipse is noteworthy because it typifies attitudes current then and still circulating in some quarters for decades afterwards. Contrasting the inchoate observations of his respondants, the episode illustrates Airy's own desire to quantify the measurement of light, to make it more in accord with what he saw as the changing status of other scientific subjects.[8] Light measurement was increasingly being portrayed as a subject out of step with modern science. In 1911, the engineer Alexander Trotter observed:

> The study of light, its nature and laws, belongs to the science of optics, but we may look to optical treatises in vain for any useful information on [the distribution and measurement of light]. Illumination, if alluded to at all, is passed over in a few lines, and it has remained for engineers to study and to work out the subject for themselves.[9]

This perceived disjunction – jarring, at least, for engineers infused with the new fashion for quantification – was not restricted to practitioners of optics. Writing as late as 1926, the Astronomer Royal for Scotland, Ralph Allen Sampson (1866-1939), complained of the provisional character still maintained by astronomical photometry:

> One is apt to forget that the estimation of stellar magnitudes is coeval with our earliest measures of position. . . . The six magnitudes into which we divide the naked eye stars are a legacy from. . . sexagesimal arithmetic. The subsequent development of the two is in curious contrast. The edifice of positional astronomy is the most extensive and the best understood in all science, while light measurement is only beginning to emerge from a collection of meaningless schedules.[10]

Indeed, the quantitative measurement of light intensity was not commonplace until the 1930s. To modern observers, usually imbued with a strong faith in the merits of numbers, it may seem anomalous that scientists and engineers came routinely to measure such an ubiquitous attribute as the brightness of light so long after quantification had become central to other fields of science.[11] Why was it seen as being so decoupled from the observational criteria of other, seemingly similar, subjects? In the study of light alone, for example, 18th century investigators took great care in measuring refractive indices. They also cultivated theories of image formation, comparing their predictions with precise observation. In observational astronomy, the refinement of angular, positional and temporal measurement underwent continual development. Practitioners of these numerate subjects strove to improve the precision of their measurements. In astronomy, clocks were improved, angle-measuring instruments made more precise, and the vagaries of human observation reduced.[12] Even practitioners of the considerably less analytical subject of physiology conformed to evolving practice, readily adopting the routine quantitative measurement of variables such as respiration and pulse rate in the mid 19th century. By contrast, light measurement was characterised by a range of approaches and precisions through the 19th century.[13] Why did those interested in characterising light resist a quantitative approach, and what were their motivations ultimately for adopting such methods? How fundamental or 'natural' was the resulting numerical system?[14] How, too, was the course of the subject determined by its segmentation between separate communities?[15]

This book explores the ideas and practice of light measurement from the 18th to the late 20th century, and discusses the factors influencing its development. I argue that the answers to these questions relate primarily to the particular <u>*social*</u> development of light measurement practices, and, to a more limited extent, to the little appreciated technical difficulties of photometry. Underlying the cases examined is the question: why was the subject mathematised at all? As Simon Schaffer has observed, 'Quantification is not a self-evident nor inevitable process in a science's history, but possesses a remarkable cultural history of its own'.[16] Moreover, quantification is not value-free, and 'the values which experimenters measure are the result of value-laden choices'. Thus:

> Social technologies organize workers to make meaningful measurements; material technologies render specific phenomena measurable and exclude others from consideration; literary technologies are used to win the scientific community's assent to the significance of these actions.[17]

He suggests, however, that the spread of a quantifying spirit is linked ultimately with the formation of a single discipline of measurement, that is, a universally employed technique and interpretation of the results. By contrast, I argue that quantitative measurement can spread even in such culturally and technically fragmented subjects as light measurement, and support this view with an examination of the industries and scientific institutions emerging during the late 19th and early 20th centuries that became involved with the subject. The diffused distribution of light measurement between technical subcultures is important in itself. Svante Lindqvist has called the 'historiographical threshold' the level of fame that must be exceeded to attract the interest of historians. This book supports his argument that the 'middle' levels of science are worthy of attention, and that 'the network itself may be more important than its nodes'.[18]

Organisation of chapters

The book explores different levels and nodes of the network of light measurement in separate chapters. Chapter 2 traces early interest in the measurement of light intensity. Work in the 18th century by cautiously optimistic observers such as Pierre Bouguer, Johann Lambert and Benjamin Thompson was intermingled with more dismissive publications by their contemporaries. The subject was essentially re-invented to suit each successive investigator. What motivated this work, and how was it expressed? Bouguer's interest derived from a concern about the effect of the atmosphere on stellar magnitudes; Lambert's, from a desire to extend the analytical sciences to matters concerning the brightness of light; Thompson's, from a wish to select an efficient lamp and to design improved illumination for buildings. A second factor in contemporary responses was the deceptive simplicity of intensity measurement. In making their measurements, early practitioners commonly denied physiological relationships limiting the eye's perception of brightness. Their variable results consequently attributed a poor reputation to the subject. The more careful of the early investigators refined observing techniques to minimise the effects of the changes they noted in the sensitivity of the eye.

The 19th century witnessed profound changes in the manner in which science was practised. This was true also in the particular case of the practice, and attitudes towards the value, of light measurement. A survey of papers published on the general subject of light measurement shows an acceleration in publication towards the end of the century; its rate of increase was considerably greater than for more established subjects such as gravitational research or the standardisation of weights and measures. What distinguished the work of this period from earlier investigations? Chapter 3 discusses the late 19th century as a crucial period in the gradual transition from qualitative to quantitative methods in the measurement of light. Despite the enthusiasm of a few proselytisers like William Abney, who published prolifically on every aspect and application of light measurement, general interest remained restrained. Part of the reason remained the difficulties imposed by vision itself. The human eye was increasingly identified as a very poor absolute detector of light intensity. The perception of brightness was found to vary with colour, the mental and physical condition of the observer, and the brightness itself. By the first decade of the 20th century practitioners had evolved a thorough mistrust of 'subjective' visual methods of observation and inclined towards 'objective' physical methods that relied upon chemical or electrical interactions of light. This simplistic identification of 'physical' as 'trustworthy, unbiased and desirable' came to be a recurring theme in the subject. The rejection of visual methods for physical detectors was nevertheless a matter of scientific fashion having insecure roots in rational argument.

A major factor in the trend towards the acceptance of quantitative methods was the demonstration of the benefits of numerical expression. Among the first practical motivations for measuring the brightness of light were the utilitarian needs of the gas lighting industry. Photometers in use by gas inspectors outstripped those available in universities in the late 19th century. The nascent electric lighting industry began to seek a standard of illumination, too, by the early 1880s. The comparison of lamp brightnesses and efficiencies was an important factor in the marketing and commercial success of numerous firms. A major incentive for standards of brightness thus came from the electric lighting industry. So intimately did electric lighting and photometry become linked that practitioners of the art were as often drawn from the ranks of electrical engineering as from optical physics.

During the same period, independent researchers increasingly proposed systems of colour specification or measurement. Most had a practical interest in doing so. The principal goal of these early investigators was the development of empirical means of using colour for systematic applications.[19] The invention and use of such systems by artists, brewers, dye manufacturers and horticulturalists is evidence both of the creation of a strong practical need for metrics of light and colour measurement, and of lack of interest in academic circles. The utilitarian incentive for light and colour specification was thus a driving force in establishing a more organised practice of light measurement near the end of the century.

The benefits of light measurement were increasingly heralded and applied to industrial and scientific problems between 1900 and 1920. Professional scientists, engineers and technicians specialising in these subjects appeared during this time. Just as importantly, the 'illuminating engineering movement' became an influential community for the subject, with dedicated societies being organised in America and Europe. Here again, social questions are of central concern: how and why did such communities foster a culture of light measurement? The transition from gentlemen amateurs to lobbyists is discussed in Chapter 4.

Sensitive to the growing needs of government and industry alike, the national laboratories founded in Germany, Britain and America between 1887 and 1901 were tasked with responsibility for setting standards of light intensity and colour. Broader cultural questions begin to emerge: why did these institutions soon come to influence all aspects of photometry? How did the centre of control shift from the domain of individuals and engineering societies to state-supported investigation? Academic research was affected through the development of measurement techniques; government policy, by the recommendation and verification of illumination standards; and industry, by defining norms of efficiency and standards for quality control. This is a case of the pursuit of utilitarian advantages leading to fundamental research: the search for a photometric standard broadened to the study of radiation from hot bodies, and thence to Planck's theory of 'blackbody' radiation. Chapter 5 centres on the important influence of the national laboratories on the subject.

From the turn of the century, photometric measurements increasingly used photographic materials in place of the human eye. With two types of detector available – the human eye and photographic materials – investigators could now quantify light in two distinct ways. On the one hand, light could be measured in a 'physical' sense – that is, as a quantity of energy similar to electrical energy or heat energy. On the other hand, light could be measured by its effect on human perception. Disputes over the characterisation of this ***perceptual*** sense as 'psychological', 'psychophysical' or 'physical' are discussed in Chapter 7. The disparity between these two viewpoints, scarcely noticed in the preceding decades, was to introduce problems for both that remained unresolved for years.

The investigation of the photoelectric effect had been a convincing demonstration of the value of quantitative measurement in academic circles. From the 1920s, the development of new photoelectric means of measuring light intensity led to commercial instruments. This trend accelerated in the next decade, when engineers and chemists applied photometric measurement with limited success to a range of industrial problems. The successive transition between visual, photographic and photoelectric techniques was fraught with technical difficulties, however. As Bruno Latour has discussed, the 'black-boxing' of new technologies can be a complex and socially determined process. A central problem concerned the basing of standards of brightness on highly variable human observers, and on the complex mechanism of visual perception. Other problems revolved around the use of photographic and photoelectric techniques near the limits of their technology, and yet important to human perception of light or colour. While some of these difficulties submitted to technological solutions, others were evaded by setting more accessible goals and by recasting the subject. Chapter 6 centres on the rapid technological changes that transformed photometry in the inter-war period.

The technical evolution was frequently subservient to, and directed by, cultural influences. The inter-war period witnessed the dominance of technical delegations in constructing the subjects of photometry and, even more self-consciously, colorimetry. There was a profound conflict between a psychological approach based on human perception, and a physical approach based on energy detectors. The subject suffered from being of interest to intellectual groups having different motivations and points of view – so much so that the only resolution was by inharmonious compromise. Chapter 7 argues that the social and political climate between the world wars significantly influenced the elaboration and stabilisation of these subjects.

Seeds sown in the 1920s were to be cultivated in the following decade. A 'fever of commercialised science' (as one physicist put it) was invading not only industry, but also academic and government institutions. Links between government laboratories and commercial instrument companies strengthened. Industrialists were imbued with the values of quantification by the commercial propaganda of large companies. The drive towards industrial applications faltered before the Second World War, however, owing to mistrust after the overoptimistic application of the principles of quantification. Plant managers and industrial chemists were to complain that their new photoelectric meters could not adequately quantify the many factors affecting the brightness or colour of a process or product. The previously simplistic and positive view of quantification was supplanted by a more cautious approach. These early efforts to commercialise light measurement are explored in Chapter 8.

The closer identification of science with military technology was an outcome of the Second World War. Radiometry consequently was well funded in the post-war years, and carried innovations to the now 'cognate subjects' of photometry and colorimetry. Chapter 9 discusses the effects on technical practice and social organisation.

Chapter 10 explores the general historical features of the subject of light measurement. The creation of a quantitative perspective, the development of measurement techniques, the organisation of laboratories and committees and the design of commercial instruments can be discussed most profitably from a perspective that emphasises the social and intellectual interactions.[20] This approach supports the view that dichotomies such as ‘technology/science’, ‘internal/external technical history’ and ‘pure/applied science’ are inadequate to understand this topic. Indeed, the history of light measurement provides evidence for the statement by Bijker, Hughes and Pinch that ‘many engineers, inventors, managers and intellectuals in the 20th century, especially in the early decades, created syntheses, or seamless webs’.[21] Rather than discussing compartmentalised disciplines and well-articulated motivations, these authors portray science as a complex interplay of cultural and technological forces. Engineers, scientists, committees, institutions, technical problems and economic factors combined in complex ways to shape the subject of light measurement. The subject can be related in these respects to quite different scientific endeavours. A quotation from a paper on the regulation of medical drugs illustrates the commonality found also in the subject of light measurement:

> The stabilisation of technological artifacts is bound up with their adoption by relevant social groups as an acceptable solution to their problems. Such groups. . . may be dispersed over social networks. [This] involves complex processes of social management of trust. People must agree on the translation of their troubles into more or less well delineated problems, and a proposed solution must be accepted as workable and satisfactory by its potential users and must be incorporated into actual practice in their social networks.[22]

The importance of traditions of device design, important in the present study, have recently been analysed in a different context. Peter Galison has written extensively on the history of microphysics, and has argued persuasively that instrumentation has been a central factor in the emergence of distinct scientific subcultures.[23] The growing experimental complexity of all these instruments created an almost impenetrable wall between experimental traditions. Researchers could no longer cross over from one methodology to the other, or even fully understand each other. Those scientific workers at the boundaries between sub-cultures of measurement, or between theory and experiment, military and civilian science, had to develop local languages – pidgins and creoles – to translate between them. This fertile analogy works very well for what Galison to some extent disparages but acknowledges to be a seductive and ubiquitous idea in science studies: the notion of science as “island empires, each under the rule of its own system of validation”.[24] The present book explores the emergence, coalescence and decay of subcultures closer to the borders or recognised science.

The subject of light measurement is a particular case of a more general socially mediated process. But in addition to this, as mentioned above, the subject has skirted the periphery of science and evades easy definition. Light measurement can be interpreted as a case of an ‘orphan’ or ‘peripheral’ science neglected both by engineers and academic scientists. Although not typical of the cases studied by historians of science, it is nevertheless representative of a wide and flourishing body of activities that attained importance in the 20th century.

My operational definition of peripheral science includes the following characteristics:

- a lack of 'ownership' of, and authority over, the subject by any one group of practitioners;
- a persistent straddling of disciplinary boundaries;
- absence of professionalisation by practitioners of the subject;
- a shifting interplay between technology, applied science and fundamental research that resists reconciliation into a coherent discipline.

Peripheral sciences are not merely the applied science and technology that have dominated the 20th century, but a particular class of such subjects. Focusing on French and German developments, Terry Shinn has discussed a class of similar subjects under the name 'research technologies'. Lacking easy definition, these have hitherto been little studied by either historians of science or historians of technology. Nevertheless, many subjects in modern science and technology are demonstrably of this class and would profitably be treated in these terms. I shall return to these ideas in Chapter 10 to explore the value of this designation as an explanatory idea in the history of modern science and technology.

Terms

The terminology employed in this subject is frequently opaque. Researchers concerned with light measurement have fallen into three distinct camps, each measuring intensity for its own reasons, using methods developed at least partially in isolation from the other two distinct groups of practitioners. These three camps were (and are) *photometry*, *colorimetry* and *radiometry*. The precise definitions of these terms have varied over the decades, but can be approximated as follows: photometry deals with the measurement of the intensity of visible light; colorimetry involves the measurement or specification of colour or coloured light; and, radiometry refers to the measurement of non-visible radiation such as infrared and ultraviolet 'light'. The grouping together of these subjects is a modern construct, because the practitioners have generally mixed them only peripherally, and only in a concerted way since the 1930s. The interaction and eventual merging of these subjects is, however, one of the threads traced in this work. For convenience, I will generally use these terms and *light measurement* interchangeably whether the measurement of visible, coloured or invisible 'light' intensity is concerned, except where I refer to a specific topic.

A more central terminological problem relates to discussion of the amount of light itself. Since standards of light measurement were first discussed in the last decades of the 19th century, a detailed terminology has evolved to differentiate between, for example, the measurement of light emitted by a source, falling on a surface, radiated into a given solid angle or perceptible to an average human eye. The respective terms and definitions have changed as national standards and languages clashed. Some of the historical confusion surrounding the definition of these quantities is discussed in Chapter 7. For the purposes of this work, though, all of these are aspects of the central problems of determining *how much* light is present at some location or *how concentrated* it is, i.e. of quantity and intensity, respectively. Early practitioners often used the term *luminosity* and the unit *candle-power* for the intrinsic brightness of a light source. Following the lead of one of the first writers on photometry, Pierre Bouguer, I employ two general ideas. First, I use the term *quantity of light* to refer to the light reaching either the human eye or the variety of physical detectors that have come into use since 1870. This idea, called by convention *flux* in modern terminology, represents the total amount of light reaching the detector by integrating over the field of view of the detector, or over the range of wavelengths to which it is sensitive, or over the area that the light illuminates in unit time.[25] Secondly, I use the terms *intensity* or *brightness* to refer to the concept of variations in perceived brightness. Intensity is a measure of the *concentration* or *density* of light in some sense. A lens can focus a given quantity of light to a more intense spot of smaller area, making it brighter. Intensity can thus be represented as a quantity of light per unit area, or per unit solid angle, or per wavelength range. In modern terminology these are distinguished by the names *illuminance*, *radiance* or *spectral flux*. While these distinctions are not crucial to the content of this book, the non-intuitive basis of these terms encapsulates some of the complexities faced by practitioners of the subject.

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[1] 'Suggestions for observation of annular eclipse of the sun, 1858, March 14-15', *Mon. Not. Roy. Astron. Soc.* **18** No 4 129; 'Observations of the annular solar eclipse', *Mon. Not. Roy. Astron. Soc*. **18** No 5 184.

[2]*Ibid.* 188.

[3]*Ibid.* 184.

[4]Glaisher, appointed in 1833 as Airy's second assistant, was an early advocate of meteorology and an innovator in photography.

[5]*Mon. Not. Roy. Astron. Soc.* **18** No 5 196-197.

[6]For an account centring on transits of Venus, see Rothermel H 1993 'Images of the sun: Warren De la Rue, George Biddell Airy and celestial photography', *BJHS* **26** 137-69.

[7]*Mon. Not. Roy. Astron. Soc.* **18** No 4131.

[8]Indeed, even in other aspects of optics such as the angular measurement of diffraction fringes.

[9]Trotter A P 1911 *Illumination: Its Distribution and Measurement* (London) p 1.

[10]Sampson R A 1926, 'The next task in astronomy', *Proc. Opt. Convention 2* 576-83; quotation p. 576.

[11]For 17th and 18th century roots of 'l'esprit géométrique', see Frängsmyr Heilbron T J L and Rider R E (eds.) 1990 *The Quantifying Spirit in the Eighteenth Century* (Berkeley).

[12]Differences in the 'personal equation', relating an observer's muscular reflex to aural and visual cues, were minimised by various observational techniques and instrumental refinements. See, for example, Schaffer S 1988 'Astronomers mark time: discipline and the personal equation', *Sci. Context* **2** 115-45.

[13]See, for example, Olesko K M & Holmes F L 1993 'Experiment, quantification and discovery: Helmholtz's early physiological researches, 1843-50', in: D. Cahan (ed) 1993, *Hermann von Helmholtz and the Foundations of Nineteenth-Century Science* (Berkeley) pp 50-108.

[14]Philip Mirowski, for example, has concluded that measurement standards and seemingly 'natural' schemes derived by dimensional analysis are tainted by anthropomorphism: 'measurement conventions – the assignment of fixed numbers to phenomenal attributes – themselves are radically underdetermined and require active and persistent intervention in order to stabilize and enforce standards of practice' [Mirowski P 1992 'Looking for those natural numbers: dimensionless constants and the idea of natural measurement', *Sci. Context* **5** 165-88; quotation p 166].

[15]Thomas Kuhn defined a *community* as a group that shares adherence to a particular scientific 'paradigm' [Kuhn T 1970 *The Structure of Scientific Revolutions* (Chicago, 2nd ed) p 6]. I have used the term to label a loosely-knit group that, while sharing common goals, methods or vocational backgrounds, is not as firmly centred on a core-set of knowledge and self-policing activities as is a *discipline*. This distinction is discussed further in Chapter 10.

[16]Schaffer 1988, *op. cit.* 115.

[17]*Ibid.* 118.

[18]Lindqvist S 1993 'Harry Martinson and the periphery of the atom' in: Lindqvist S (ed) 1993 *Center on the Periphery: Historical Aspects of 20th-Century Physics* (Canton) pp ix-lv.

[19]Ames Jr A 1921 'Systems of color standards', *JOSA* **5** 160-70.

[20]For an overview of the 'first wave' of sociological studies, see Merton R K and Gaston J (eds.) 1977 *The Sociology of Science in Europe* (Carbondale). For more recent introductions, see Collins H M 1982, *Sociology of Scientific Knowledge: A Source Book* (Bath) and Barnes B & Edge D 1982 *Science in Context* (Milton Keynes).

[21]Bijker W E, Hughes T P & Pinch T J (eds) 1987 *The Social Construction of Technological Systems* (Cambridge, MA: MIT Press) p 9.

[22] Bodewitz H J, Buurma H and de Vries G H, 'Regulatory science and the social management of trust in medicine', in *ibid*. 217.

[23]Galison P L 1997 *Image and Logic: A Material Culture of Microphysics* (Chicago).

[24]*Ibid.* 12.

[25]The term *quantity of light* is sometimes used to mean the total amount in a given time period, i.e. the *time integral* of flux. The difference between these two meanings will be clear from the context.