A Notion or a Measure: The Quantification of Light to 1939

by

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Submitted in accordance with the requirements for the degree of

Doctor of Philosophy

The University of Leeds

Department of Philosophy

Division of History and Philosophy of Science

November, 1994

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

Abstract

This study, presenting a history of the measurement of light intensity from its first hesitant emergence to its gradual definition as a scientific subject, explores two major themes. The first concerns the adoption by the evolving physics and engineering communities of quantitative measures of light intensity around the turn of the twentieth century. The mathematisation of light measurement was a contentious process that hinged on finding an acceptable relationship between the mutable response of the human eye and the more easily stabilised, but less encompassing, techniques of physical measurement.

A second theme is the exploration of light measurement as an example of 'peripheral science'. Among the characteristics of such a science, I identify the lack of a coherent research tradition and the persistent partitioning of the subject between disparate groups of practitioners. Light measurement straddled the conventional categories of 'science' and 'technology', and was influenced by such distinct factors as utilitarian requirements, technological innovation, human perception and bureaucratisation. Peripheral fields such as this, which may be typical of much of modern science and technology, have hitherto received little attention from historians.

These themes are pursued with reference to the social and technological factors which were combined inextricably in the development of the subject. The intensity of light gained only sporadic attention until the late nineteenth century. Measured for the utilitarian needs of the gas lighting industry from the second half of the century, light intensity was appropriated by members of the nascent electric lighting industry, too, in their search for a standard of illumination. By the turn of the century the 'illuminating engineering movement' was becoming an organised, if eclectic, community which promoted research into and standards for the measurement of light intensity.

The twentieth-century development of the subject was moulded by organisation and institutionalisation. Between 1900 and 1920, the new national and industrial laboratories in Britain, America and Germany were crucial in stabilising the

subject. In the inter-war period, committees and international commissions sought to standardise light measurement and to promote research. Such government- and industry-supported delegations, rather than academic institutions, were primarily responsible for the ‘construction’ of the subject. Practitioners increasingly came to interpret the three topics of *photometry* (visible light measurement), *colorimetry* (the measurement of colour) and *radiometry* (the measurement of invisible radiations) as aspects of a broader study, and enthusiastically applied them to industrial and scientific problems.

From the 1920s, the long-established visual methods of observation were increasingly replaced by physical means of light measurement, a process initially contingent on scientific fashion more than demonstrated superiority. New photoelectric techniques for measuring light intensity engendered new commercial instruments, a trend which accelerated in the following decade when photometric measurement was applied with limited success to a range of industrial problems. Seeds sowed in the 1920s – namely commercialisation and industrial application, the transition from visual to ‘physical’ methods, and the search for fundamental limitations in light measurement – gave the subject substantially the form it was to retain over the next half-century.

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Abbreviations

The following abbreviations are used in the footnote references and bibliography.

Periodicals:

Am. J. Sci.	American Journal of Science
Am. J. Phys.	American Journal of Physics
Ann. Harvard Coll. Obs.	Annals of the Harvard College Observatory
Ann. Physik	Annalen der Physik
Ann. Sci.	Annals of Science
Appl. Opt.	Applied Optics
Arch. Hist. Exact Sci.	Archive for the History of the Exact Sciences
Arch. Int. Hist. Sci.	Archives Internationales d'Histoire des Sciences
Astron. & Astrophys.	Astronomy & Astrophysics
Astrophys. J.	Astrophysical Journal
Biog. Mem. Nat. Acad. Sci.	Biographical Memoirs of the National Academy of Sciences of the USA
BJHS	British Journal for the History of Science
Brit. J. Psychol.	British Journal of Psychology
Bull. Bur. Standards	Bulletin of the Bureau of Standards
Bull. Hist. Élec.	Bulletin d'histoire de l'électricité
Bull. Sci. Instr. Soc.	Bulletin of the Scientific Instrument Society
Bur. Stan. J. Res.	Bureau of Standards Journal of Research
Bus. Hist. Rev.	Business History Review
Chem. Age	The Chemical Age
Chem. Eng. Works Chemist	Chemical Engineering and the Works Chemist

Coll. Res. NPL	Collected Researches of the National Physical Laboratory
Comptes Rendus	Comptes Rendus hebdomadaires des séances de l’académie des sciences
Compte Rendu CIE	Recueil des Travaux et Compte Rendu des Séances de la Commission Internationale de l’Éclairage
Daedalus	Daedalus
DNB	Dictionary of National Biography
DSB	Dictionary of Scientific Biography
Elec. Perspectives	Electrical Perspectives
Electrician	The Electrician
GEC Rev.	GEC Review
Hist. Sci.	History of Science
Hist. Stud. Phys. Sci.	Historical Studies in the Physical Sciences
Hist. Stud. Phys. Biol. Sci.	Historical Studies in the Physical and Biological Sciences
Hist. Technol.	History of Technology
Ind. & Eng. Chem.	Industrial and Engineering Chemistry
Indus. Chemist	The Industrial Chemist
Illum. Engineering	Illuminating Engineering
Illum. Eng.	The Illuminating Engineer (London)
Illum. Eng. (NY)	The Illuminating Engineer (New York)
Infr. Phys.	Infrared Physics
Isis	Isis
J. Am. Chem. Soc.	Journal of the American Chemical Society
J. de Phys.	Journal de Physique
J. Franklin Inst.	Journal of the Franklin Institute
J. Gas Lighting	Journal of Gas Lighting

J. Hist. Astron.	Journal of the History of Astronomy
J. Indus. & Eng. Chem.	Journal of Industrial and Engineering Chemistry
J. IEE	Journal of the Institute of Electrical Engineers
J. Res. NBS	Journal of Research of the National Bureau of Standards
J. Sci. Instr.	Journal of Scientific Instruments
JOSA	Journal of the Optical Society of America
JOSA & RSI	Journal of the Optical Society of America and Review of Scientific Instruments
J. Vac. Sci. Tech.	Journal of Vacuum Science & Technology
Lum. Élec.	La Lumière Électrique
Minerva	Minerva
Mon. Not. Roy. Astron. Soc.	Monthly Notices of the Royal Astronomical Society
Mém. Acad. R. des Sci. Paris	Mémoires de l'Académie Royale des Sciences de Paris
Mind	Mind
Nat. Acad. Sci. Proc.	National Academy of Science Proceedings
NPL Report	National Physical Laboratory Report for the Year
Nature	Nature
Obit. Not. Roy. Soc.	Obituary Notices of Fellows of the Royal Society of London
Opt. & Phot. News	Optics and Photonics News
Osiris	Osiris
Phil. Mag.	Philosophical Magazine
Phil. Trans. Roy. Soc.	Philosophical Transactions of the Royal Society of London
Photog. Indus.	Photographic Industry
Photog. J.	Photographic Journal
Photog. News	Photographic News

Phys. Rev.	Physical Review
Phys. Today	Physics Today
Proc. Am. Acad. Arts. Sci.	Proceedings of the American Academy of Arts and Sciences
Proc. IEE	Proceedings of the Institute of Electrical Engineers
Proc. Opt. Convention	Proceedings of the Optical Convention
Proc. Phys. Soc.	Proceedings of the Physical Society of London
Proc. Roy. Astron. Soc.	Proceedings of the Royal Astronomical Society
Proc. Roy. Soc.	Proceedings of the Royal Society of London
Proc. Roy. Soc. Edin.	Proceedings of the Royal Society of Edinburgh
Rev. Opt.	Revue d'Optique
Rev. Sci. Instr.	Review of Scientific Instruments
Sci. Context	Science in Context
Sci. Stud.	Science Studies
Soc. Sci. Res.	Social Science Research
Soc. Stud. Sci.	Social Studies in Science
Technol. & Culture	Technology and Culture
Trans. Illum. Eng. Soc.	Transactions of the Illuminating Engineering Society of London
Trans. Illum. Eng. Soc. (NY)	Transactions of the Illuminating Engineering Society of New York
Trans. Opt. Soc.	Transactions of the Optical Society

Organisations:

BCC	British Colour Council
BEMA	British Electrical Manufacturers Association
BESA	British Engineering Standards Association
BSIRA	British Scientific Instruments Research Association
CIE	Commission Internationale de l'Éclairage
CIP	Commission Internationale de Photométrie
DSIR	Department of Scientific and Industrial Research
ELMA	Electric Light Manufacturers Association
GEC	General Electric Company (UK)
IRC	International Research Council
ISCC	Inter-Society Color Council (USA)
NBS	National Bureau of Standards (USA)
NELA	National Electric Lamp Association (USA)
NPL	National Physical Laboratory (UK)
OSA	Optical Society of America
PTR	Physikalisch-Technische Reichsanstalt

Where. . . is there an office scientifically enough illuminated to be the happy hunting ground of a man intent on writing a research thesis?

Anon. editorial, *Electrical Review*, Sep. 6, 1907.

Acknowledgements

I would like to thank my supervisor, Geoffrey Cantor, for his warm encouragement and helpful advice. Thanks, too, to Graeme Gooday, Colin Hempstead, Arne Hessenbruch, Jeff Hughes, Andrew Warwick and others for their suggestions, discussions and/or interest in my chosen subject. Charles Amick, Dick Fagan and William Hanley of the Illuminating Engineering Society of North America, Susan Farkas of the Edison Electric Institute, David MacAdam at the Institute of Optics in Rochester, Deborah Warner of the Smithsonian Institution, and the librarians of the Edward Boyle and Brotherton Libraries at the University of Leeds helped me to locate source material. I am grateful, also, to Charles Thomas Whitmell, whose name appeared with surprising regularity as the collector of documents I searched at Leeds.[1]

I dedicate this work to my family: to my parents, who planted the seeds of my interests; to my wife Libby, who nurtured them and supplied constant support and encouragement; and to my son Daniel. I give them my love and thanks.

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[1] C. T. Whitmell, born 1849, Leeds; MA (Cambridge, 1875); schoolmaster 1876-1878; Inspector of Schools 1879-1910; author, *Colour: An Elementary Treatise* (London, 1888); died 1919, Headingley.

Chapter 1
Introduction

In the February 1858 issue of the *Monthly Notices of the Royal Astronomical Society*, the Astronomer Royal, George Biddell Airy, set out a programme to observe the forthcoming partial solar eclipse. Among other tasks, he asked 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’.[2]

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’.[3] 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’.[4] 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

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[2]*Mon. Not. Roy. Astron. Soc.* 18, Nos. 4 and 5.

[3]*Ibid.*, p. 188.

[4]*Ibid.*, p. 184.

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.[5] 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’.[6]

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.[7] 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’,[8] 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.

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

[6]*Mon. Not. Roy. Astron. Soc.* 18, p. 196-197.

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

[8]*Mon. Not. Roy. Astron. Soc.* 18, p. 131.

Glaisher and others monitored temperature to 0.1° F, but did not attempt to analyse their data to infer changes in intensity.

The records of the 1858 eclipse indicate the value that these astronomical observers placed on quantitative intensity data. There was no consensus on what methods were relevant, nor on what degree of 'quantification' was useful. Nowhere in Airy's article or his respondents' accounts was a clear *purpose* 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 relative apparent areas of the solar and lunar disks, 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-nineteenth century observers to bring such standards to the measurement of light intensity . The observers supplied Airy's request by obtaining merely *a notion* instead of *a measure* 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. Techniques for measuring the intensity of light, and interest in doing so, were curiously slow in developing when compared with practice in other scientific subjects.[9] 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.[10]

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

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

The lack of interest was not restricted to practitioners of optics. Writing as late as 1926, the Astronomer Royal for Scotland, Ralph 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.[11]

Indeed, the quantitative measurement of light intensity was not commonplace until the 1930s. At first sight it seems 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.[12] Why was it so out of step with other, seemingly similar, subjects? In the study of light alone, for example, eighteenth 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.[13] By contrast, light measurement was characterised by a range of approaches and precisions through the nineteenth century. Even practitioners of the considerably less analytical subject of physiology readily adopted the routine quantitative measurement of variables such as respiration and pulse rate in the mid nineteenth century, decades before an

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

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

[13] 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, S. Schaffer, 'Astronomers mark time: discipline and the personal equation', *Sci. Context* (1988) 2, 115-45.

analogous consensus in photometry.[14] Why were practitioners of light measurement so hesitant in adopting a quantitative approach, and what were their motivations ultimately for doing so? How fundamental or 'natural' was the resulting numerical system?[15] How, too, was the course of the subject determined by its segmentation between separate communities?[16]

In this thesis I explore the ideas and practice of light measurement from the eighteenth century to the Second World War, and discuss the factors influencing its development. I propose that the answers to these questions relate primarily to the particular *social* 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'.[17] 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

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

[15]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' [P. Mirowski, 'Looking for those natural numbers: dimensionless constants and the idea of natural measurement', *Sci. Context* 5 (1992), 165-88; quotation p. 166].

[16]Thomas Kuhn defined a *community* as a group that shares adherence to a particular scientific 'paradigm' [Kuhn, *The Structure of Scientific Revolutions* (Chicago, 2nd ed, 1970), 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 9.

[17]Schaffer, *op. cit* [12]., 115.

> others from consideration; literary technologies are used to win the scientific community's assent to the significance of these actions.[18]

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.[19] I contend, rather, that quantitative measurement can spread even in such culturally and technically fragmented subjects as light measurement. I support this view with an examination of the industries and scientific institutions emerging during the late nineteenth and early twentieth centuries that became involved with light measurement. In parallel with, and linked to, this social history, I discuss the growth of scientific interest in the limitations of human visual perception, and the subsequent efforts to develop a physical means to detect light intensity.

Chapter 2 traces early interest in the measurement of light intensity. Work in the eighteenth century by careful observers such as Pierre Bouguer, Johann Lambert and Benjamin Thompson was intermingled with more hasty or presumptive publications by their contemporaries, and was little appreciated. 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, to 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 the lack of interest was the deceptive simplicity of intensity measurement. In making their measurements, many of the early practitioners overlooked complicated relationships affecting the eye's perception of brightness. Their unreliable results consequently attributed a poor reputation to the subject. The more careful of the early investigators developed observing techniques to minimise the effects of the changes they discovered in the sensitivity of the eye.

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[18]*Ibid.*, 118.

[19]*Ibid.*: 'The formation of a *discipline* is simultaneously the process of organizing work to produce these values and the system of knowledge which gives the values their meaning'.

The nineteenth 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 through the nineteenth century shows a gradual increase with time, accelerating near the end of the century. Its rate of increase was greater than for more established subjects such as gravitational research or the standardisation of weights and measures.[20] What distinguished the work of this period from earlier investigations? Chapter 3 discusses the late nineteenth 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 proved to be a very poor absolute detector of light intensity. The perception of brightness was found to vary with colour, the condition of the observer, and the brightness itself. By the first decade of the twentieth 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 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 nineteenth 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

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[20]See Appendix I.

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.[21] The invention and use of such systems by artists, brewers, dye manufacturers and horticulturalists is evidence both 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.

Between 1900 and 1920, the benefits of light measurement were increasingly heralded and applied to industrial and scientific problems. 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 major 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.

The national laboratories founded in Germany, Britain and America between 1887 and 1901, sensitive to the growing needs of government and industry alike, 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. Contrary to the models of the development of scientific subjects commonly treated by historians of science, in this case the evident utilitarian advantages led to fundamental

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

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.[22] The disparity between these two viewpoints, scarcely noticed in the preceding decades, was to introduce problems for both, and to remain 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.

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[22] Disputes over the characterisation of this *perceptual* sense as 'psychological', 'psychophysical' or 'physical' are discussed in Chapter 7.

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. The conflict between a psychological approach based on human perception, and a physical approach based on energy detectors, was profound. 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. I argue in Chapter 7 that the elaboration and stabilisation of these subjects between the World Wars were significantly influenced by the social and political climate.

Seeds sowed in the 1920s – namely commercialisation and industrial application, the growing trend from visual to ‘physical’ measurement, and the search for fundamental limitations in light measurement – 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 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.

In Chapter 9, I discuss 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 sociological viewpoint. A sociological orientation has been increasingly applied to scientific case studies over the past twenty years.[23] In common with these, I deal implicitly with the history of light measurement from a perspective that could broadly be described as sympathetic to the ideas of social constructivism. Drawing on elements of the ideas of historians and sociologists such as Trevor Pinch, Thomas Hughes, Bruno Latour, David Noble and John Law, my work supports their view that dichotomies such as 'technology/science', 'internal/external' and 'pure/applied' are inadequate to analyse this (and similar) topics.[24] Indeed, the history of light measurement provides evidence for their statement that 'many engineers, inventors, managers and intellectuals in the twentieth century, especially in the early decades, created syntheses, or seamless webs'.[25] Rather than discussing compartmentalised disciplines and well articulated motivations, these authors portray science as a complex interplay of cultural and technological forces. Thomas Hughes, for example, has emphasised a 'systems approach' to understand the interactions of social entities.[26] 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

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

[24]For a synthesis of these viewpoints, see W. E. Bijker, T. P. Hughes and T. J. Pinch (eds.), *The Social Construction of Technological Systems* (London, 1987). For varied examples of cultural-technological linkages, see D. A. MacKenzie and J. Wajcman (eds.), *The Social Shaping of Technology: How the Refrigerator Got its Hum* (Milton Keynes, 1985).

[25]*Ibid.*, 9.

[26]T. P. Hughes, 'The evolution of large technological systems' in: Bijker *et. al.*, *op. cit.*, 51-82, and 'The seamless web: technology, science, etcetera, etcetera', *Soc. Stud. Sci.* 16 (1986), 281-92.

> 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.[27]

The subject of light measurement is thus a particular case of a more general socially mediated process. In addition to this, however, 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 by both 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 twentieth 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;
- generally slower and less active evolution than its scientific contemporaries.

Peripheral sciences are not merely the applied science and technology that have dominated the twentieth century, but a particular class of such subjects. 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 at greater length to these ideas in Chapter 9 to explore the value of this designation as a unifying and explanatory idea in the history of modern science and technology.

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[27]H. J. Bodewitz, H. Buurma and G. H. de Vries, 'Regulatory science and the social management of trust in medicine', in: Bijker *et. al.*, *op. cit.*, 217.

Organisation of this thesis

Scope

Any historical work must set limits that circumscribe its scope. The boundaries of this thesis are set both by social and intellectual factors. In attempting to cover the history of the subject, I have devoted relatively little space to the period prior to the mid-nineteenth century. Before then, despite seminal work by a handful of investigators, interest in light intensity was infrequent and applications few. After that time, several factors combined to increase interest in the measurement of light intensity, making it an activity of *groups* of practitioners. These factors included such disparate influences as the development of spectroscopy, astrophysics, concern for the scientific foundations of photography, and competition between gas and electric lighting systems. As the other temporal extreme, I have taken the year 1939 as the terminus for this dissertation. This date was chosen for reasons both internal and external to the subject itself.[28] The 'external' occurrence of the Second World War provided a change in direction for the technology of light measurement as well as a partial pause in its scientific development that was picked up six years later. Photometry after the Second World War was transformed by new technologies, a boom in commercialisation and, most importantly, new military support for fundamental research. The 'internal' event occurring at the end of the 1930s was the convergence of theory and practice for the subject of colorimetry and photometry and, to some extent, radiometry. By the end of that decade, colorimetry, photometry and radiometry had been stabilised, and were increasingly described as aspects of the same subject.[29]

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[28]While these terms have formerly been used to describe supposedly independent factors in the history of science, I use them here merely as the extreme 'intellectual' and 'social' poles in a continuum of influences.

[29]Indeed, other aspects of physical science had stabilised by the 1930s. Spencer Weart argues that the relationship between academic and industrial physics was established in the first four decades of the century, and has retained its character in the half century since. See S. R. Weart, 'The rise of 'prostituted' physics', *Nature* 262 (1976), 13-7.

A generally chronological treatment of the subject splits it fairly naturally into a discussion of factors that were relatively independent in influencing its development. Individuals were particularly important in the evolution of photometry before the twentieth century. Between then and the First World War, the formation of special interest groups such as the 'illuminating engineering movement' promoted concerted governmental and industrial research. By the war, government-supported institutions and industrial laboratories became the focus of research. International commissions advanced standards of illumination and photometry and significantly stabilised their definitions and scope from the mid 1920s. During the same period, research into photoelectric methods led to a rapid conversion from visual to physical methods of measurement. Finally, the decade before World War II witnessed the commercialisation of the subject. Each of these influences is treated in a separate chapter.[30]

As with temporal coverage, there is an inevitable geographical limit to the subjects treated. I have adopted a Eurocentric view for the period to the First World War, and dealt principally with developments in English-speaking countries thereafter. The national differences in the subject are relevant to its progress, particularly in the inter-war period, and a limited cross-cultural comparison of British, American and German research has therefore been made. The geographical concentration is, however, on those countries most involved with developments in light measurement, or at least typical of prevailing international trends. For this reason, most attention is given to developments in America and Britain, which dominated the definition of international standards between the wars and led the consolidation of the subject.

Sources

The primary sources for this work have been principally contemporary papers, articles and books. As light measurement was frequently perceived as a technique – a means to an end rather than the end in itself – it was often confined to specialist and trade journals. Nevertheless, the subject was highly fragmented, and the published sources were diverse. The most important of these were journals dealing with applied

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[30] The subject nevertheless resists facile 'periodisation', except perhaps for the pre- and post-photoelectric eras interchanged *c*1930.

science, engineering and instrumentation. *The Journal of the Optical Society of America* and *Review of Scientific Instruments* (published together between 1921 and 1929, and separately thereafter) and *Journal of Scientific Instruments*, a British journal founded in 1924, proved to be useful primary sources. The relatively small number of contributors to the subject of light measurement over the period studied has made the exhaustive study of some sources practicable. I have reviewed a half-dozen English language journals up to the Second World War, thereby providing a reasonable longitudinal survey of the subject. Publications on light measurement also were fairly frequent in laboratory reports. *NPL Report for the Year, Collected Researches of the NPL*, *Bureau of Standards Journal of Research* (later renamed *Journal of Research of the NBS*) and *GEC Review* contained the research products of these laboratories. Another major source was the *Compte Rendu des séances de la Commission Internationale de l'Éclairage*, the international body responsible for lighting standards. This account, generally published at four-year intervals, included the resolutions, minutes of meetings and lists of attendees at the CIE sessions.

Apart from journals self-described as 'scientific', trade magazines and popular accounts have also provided useful information. The practice of light measurement involved several independent communities of workers, but the self-styled 'illuminating engineers' made the strongest efforts to define the subject. *The Illuminating Engineer* (London) and *Transactions of the Illuminating Engineering Society of New York*, both founded in the early years of this century and responsible for much of the early enthusiasm for light measurement, provided considerable detail regarding the social evolution of the subject. These and similar publications such as the *Journal of the Franklin Institute* covered, among other things, work at government laboratories, commercial developments and international legal standards. Moreover, the informal tone they presented through editorials, sometimes opinionated news items and varied articles provided clues that the scientific journals omitted. The *New Products* sections of such publications helped trace the contemporary firms and technologies, as did patent records. The variety of groups concerned with light measurement, and responsible for its peripheral character, are reflected by the diversity of sources in which their activities were recorded.

Last among primary published sources, books gave a reasonably clear account of the contemporary state of the art. In most cases, such books were survey texts intended for practitioners in the field. Such texts generally provided a broad survey of the subject of intensity standards, photometric apparatus, recent references and photometric data for engineers or students of physics. Even for such seemingly 'objective' sources, the subtext has some importance: evaluation of the subjects treated (or not treated), practitioners cited, references made and techniques mentioned, all provide an implicit picture of the contemporary status of the subject. In so unstable a field (as light measurement was over most of the period covered in this thesis), books also served as powerful tools of persuasion and standardisation. The numerous texts on colour, each espousing a radically different system of metrics, are an example of this. In the absence of formal educational programmes, books were also a major source of training for many practitioners.

One of the difficulties of studying a peripheral science such as photometry is that unpublished primary source material is hard to come by. For example, the GEC Hirst Research Centre at Wembley, founded in 1919 and responsible for important developments in industrial photoelectric devices in the following decade, discarded 70 years of internal reports during a recent move.[31] These reports undoubtedly involved some of the individuals mentioned in this thesis such as Norman Campbell (a sometime employee of the NPL and GEC, and philosopher of science) and Clifford Paterson (first photometry researcher at the NPL and first director of research at GEC). A similar fate has been faced by the records of some of the relevant institutions. The Optical Society of America, in existence as a relatively prosperous and stable entity since 1916, has retained no records from its committees of the inter-war period.[32] The Illuminating Engineering Society of London, a locus for the development of the subject in Britain, eventually merged with a society of building engineers and discarded its early records. As one historian has noted, 'firms are not in business for the benefit of historians and archivists. . . [Firms may destroy their archives] because a new office block has been built, or because they have been taken over by a larger concern, or because they want to make more efficient use of the space

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[31] S. L. Cundy [director, GEC Hirst Research Centre], personal communication, 24 May, 1993.

[32] OSA president, personal communication, 29 Mar. 1994.

available'.[33] Without such primary archival sources, information has necessarily been gleaned from published company histories and by trawling through the publications of relevant journals to cross-reference information.

Biographies, except for brief necrologies, are non-existent for the workers who were important in this subject. Similarly, their notebooks, letters and other unpublished works have not, in general, been archived. The interactions between these individuals have become indirectly apparent through co-citations in articles, papers and book dedications; proceedings of question periods at conferences; and, common membership in associations and on commissions.

Clifford Paterson is an exception to most of the personalities mentioned in this thesis. Knighted and made a member of the Royal Society in later life, he was considerably more distinguished than most workers in light measurement. For the most part, these scientists published relatively few papers owing to the applied character of their work or for reasons of commercial secrecy. For the same reason, most practitioners of the subject were unlikely to have their collected works published, or to warrant even biographical sketches from the usual institutions.

Not having a moderate pool of unpublished primary source material available, it was deemed preferable to exclude the few available so as not to bias the history with ungeneralisable detail, instead relying on the published sources itemised above.[34]

Historians of science have previously little treated the general subject of light measurement. There are, of course, some relevant secondary sources dealing with particular aspects. Hans Kangro has published studies of radiometry in Germany, particularly concerning the experimental work of Heinrich Rubens and collaborators

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[33]D. S. L. Cardwell, *The Organisation of Science in England* (London, 1972), 175.

[34]The identified unpublished source materials include records at the Commission Internationale de l'Éclairage in Geneva, and files (principally post-1920) at the Illuminating Engineering Society of North America, the successor to the IES of New York. As the CIE session minutes, attendee lists and resolutions were published, there is thought to be little relevant unpublished material on file (J. Schanda [executive director of CIE], personal communication, 30 June, 1993).

surrounding Planck's radiation law.[35] Although the German development is important in the growth of radiometry and intensity standards (see Chapter 3), I relate it more fully to international developments and to the broader social and utilitarian issues. There have also been a handful of publications dealing with the earliest recorded work in photometry by Bouguer and Lambert. These fall outside the main thrust of this thesis, and moreover discuss the subjects from an 'internalist' viewpoint. Probably the most thorough general history and bibliography of photometry are contained in a chapter of the 1926 text by John Walsh, himself an important player in the field.[36] This is a positivistic account that treats superficially the then ongoing transition to photoelectric methods – a change that reshaped the subject. The techniques of astronomical photometry, which had a much larger scientific component than other usages, has been summarised historically by practising astronomers.[37] There have been, moreover, a number of retrospectives and capsule histories in journals of optics, physics and electrical engineering.[38] These are, for the most part, unsatisfactory in a historiographical sense. In most cases, such histories take the form of reminiscences or first-hand accounts of a period covering some 10 to 30 years in one of the numerous branches of the subject. Alternatively, they summarise the field in terms of the progress or inventions of an individual, institution or company. Because of the connection between 'actor' and 'playwright', and because successes are more common subjects than failures, such accounts must be suspected of bias towards a celebratory or eulogising perspective. This thesis, in contrast, attempts to uncover and inter-relate the important factors in the development of light measurement, many of which were not explicitly visible to practitioners of the

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[35]E.g. H. Kangro, *The Early History of Planck's Radiation Law* (English translation, London, 1976).

[36]J. W. T. Walsh, *Photometry* (New York, 1926).

[37]The most thorough of these are: G. Müller, *Die Photometrie der Gestirne* (Leipzig, 1897); K. Lundmark, 'Luminosities, Colours, Diameters, Densities, Masses of the Stars', in E. Hälfte (ed.), *Handbuch der Astrophysik* (Berlin, 1932), Band V, vol. 1, 210-574; and, J. Hearnshaw, *History of Astronomical Photometry* (Cambridge, forthcoming).

[38]A number of these, published in *JOSA*, *Appl. Opt.* and *Infr. Phys.*, are listed in the bibliography.

time. No attempt has been made to interpolate judgements of ‘success’ or ‘failure’ based on modern beliefs, which are themselves the product of particular cultural circumstances. The coverage also draws connections between subjects that have previously been only loosely linked and which straddle the conventional boundaries of science, technology and industry. Indeed, my assertion that photometry has been a subject moulded by technical fragmentation and by its peripheral role in science does not fit well with the types of history mentioned above.

Terms

The terminology for this subject presents a slight difficulty. Researchers concerned with light measurement have fallen into three distinct camps. Each of these measured 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) *radiometry, photometry,* and *colorimetry*. The precise definitions of these terms have varied over the decades, but can be approximated as follows: radiometry refers to the measurement of non-visible radiation such as infrared and ultraviolet ‘light’; photometry deals with the measurement of the intensity of visible light; and, colorimetry involves the measurement or specification of colour or coloured light. The grouping together of these subjects is, in some respects, a modern construct, because the practitioners have generally mixed them only peripherally, and only 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 the terms *photometry* 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 nineteenth 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 will employ two general ideas. First, I will use the term *quantity of light* to refer to the light reaching either the human eye or the variety of 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.[39] Secondly, I will 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 the distinctions are not crucial to the content of this thesis, the non-intuitive basis of these terms encapsulates some of the complexities faced by practitioners of the subject.

[39]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.

Chapter 2
The Prehistory of Light Measurement

Although the roots of photometry could be traced arbitrarily far into the past, the goal of this chapter is not to trace a lineage for the subject, but rather to show that there were many independent and *repeated* origins. The early development of light measurement was more akin to the seasonal variations of a field of scrub grass than to the growth of a branching tree. A number of loosely connected examples will illustrate the range of early attitudes, methods and uses of light measurement.

The 'prehistory' of this subject can be defined as the period characterised by a lack of social cohesion and interaction between investigators.[40] It predates social phenomena such as organised applications of photometry or the sharing of research results by like-minded individuals. Indeed, an investigator during this period who became aware of another's work was as likely to discount it as to build upon it. As a result, the period lacks any coherency in theory or practice and reveals little cumulative intellectual growth. This collection of isolated contributions to light measurement, while devoid of a unifying impetus, nevertheless evinces three general areas of research: the study of brightness, of radiant heat and of colour description.

Beginnings

Traditional but unrefined histories of science frequently cite progenitors who first enunciated modern ideas. The emergence of light measurement is unusual in that a variety of ideas co-existed for long periods; a single evolutionary line cannot meaningfully be traced. The few seventeenth and eighteenth century publications referring to the intensity of light usually took the form of untested proposals for its measurement or unsubstantiated assertions regarding its dependence on distance from

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[40]This predates activities referred to as the 'institutionalization of intellectual activity', or the 'dense interaction of persons who perform that activity' by Edward Shils ['Tradition, ecology and institution in the history of sociology', *Daedalus* 99 (1970), 760-825; quotation p. 763].

the light source.[41] Thus the Capucin cleric R. P. François-Marie, in a book on the measurement of light intensity published in 1700, proposed the construction of a scale of intensity by passing light through cascaded pieces of glass, or reflecting light repeatedly from mirrors, to diminish the light in equal steps corresponding to an arithmetic progression.[42] Others attempted to study the naturally available sources of light. Christian Huyghens reported that he compared the light of the sun with that of Sirius, looking at the sun through a long tube with a hole at the top, and making the two lights equally bright.[43] The observations were criticised by his near contemporary, Pierre Bouguer, because they were not made at the same moment with the external conditions and the state of the eye itself the same.

Bouguer (1698-1758) first wrote critically about questions of illumination in an essay published in 1729.[44] In the preface, he describes that he took up the subject after reading a memoir by J. J. d'Ortous de Mairan.[45] Mairan had attempted to show (without success) how, with a knowledge of the amount of light from the sun reaching the earth from two altitudes, the amount from other altitudes could be calculated. In a note in 1726, Bouguer initially tried to solve this specific problem, and published his successful results using the moon as subject and a candle as a comparison. From this, he developed means of attenuating light in measurable ratios. His *Essai* discusses how the brightness of light varies with distance from the light source, and discussed

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[41]J. W. T. Walsh, 'Was Pierre Bouguer the "father of photometry"?', *Am. J. Phys.* 26 (1958), 405-6.

[42]R. P. François-Marie, *Nouvelles Découvertes sur la Lumière pour la Mésurer et en Compter les Degrés* (Paris, 1700). According to W. E. K. Middleton, the author was careful to 'convince his conscience and his superiors that it is not impious to try to measure light, the gift of god' (see ref. [8], p. 47). Subsequent investigators noted a geometric rather than arithmetic progression of intensity diminution.

[43]C. Huyghens, *Cosmotheoros sive de terris coelestibus earumque ornatu conjecturae* (The Hague, 1698).

[44]P. Bouguer, *Essai d'Optique sur la Gradation de la Lumière* (Paris, 1729). See also F. H. Perrin, 'Whose absorption law', *JOSA.* 38 (1948), 72-4.

[45]J. J. d'Ortous de Mairan, *Mém. Acad. R. des Sci. Paris* (1721), 8-17.

the means of determining it.[46] Bouguer concluded that the eye was unreliable in measuring absolute brightness, and should instead be employed only to *match* two light sources.[47] To make such a comparison, he devised a 'lucimètre' consisting of two tubes to be directed at the two light sources, and converging at a paper screen viewed by the eye. To use the device, the observer pointed the two tubes towards the two sources. The light through one tube could be attenuated partially by masking its aperture until the two appeared equal. From the reduction in aperture area, the ratio of the two intensities could be judged. In an alternate version, one tube could be lengthened, so that the light reaching the screen was reduced according to the inverse-square law.

This first foray into photometry, published at the age of 31, was separated from his second work on the subject by 28 years. Bouguer spent 11 years on a voyage to Peru to measure an arc of the meridian for the Académie Royale des Sciences de

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[46]The inverse-square law of illumination appears to have been widely appreciated at least a century earlier, though, and was enunciated in various forms. See P. E. Ariotti & F. J. Marcolongo, 'The law of illumination before Bouguer (1729): statement, restatement and demonstration', *Ann. Sci.* 33 (1976), 331-40.

[47]P. Bouguer, *Traité d'Optique sur la Gradation de la Lumière*, transl. by W. E. Knowles Middleton (Toronto, 1961). Criticising the observations of Huyghens (p. 46): 'apart from the fact that this clever mathematician may not have made all the necessary distinctions between the total quantity of light and its intensity, it is only too certain that we can only judge directly the strength of two sensations when they affect us at the same instant. How can we assure ourselves otherwise that an organ as delicate as the eye is always precisely in the same state, that it is not more sensitive to a slight impression at one time than at another? And how can one remember the intensity of the first sensation when one is actually affected by the second and when an interval of several hours or even days has gone by between the two? To succeed in this determination he would have had to have recourse to an auxiliary light which he could make use of in the two observations, and which would serve as a common term of the comparison.' Deriding the methods of François-Marie (p. 47): 'His results must depend more or less on the transparency of his pieces of glass, and not only this, but on the differing state of his eyes, which would be more or less sensitive at one time than another. When his sight was a little fatigued all lights would ordinarily appear to him stronger. He would then need a greater number of pieces of glass to weaken them to the same extent. Each observer would in this way attribute a different degree of the scale to the light which he was measuring. People would not be able to agree when observing at different times or in different countries, and the measurements would never give exact ratios.'

Paris.[48] Besides writing up the results of the expedition, he afterwards published treatises on navigation and ships. His practical experiences had considerable relevance to his formulation of photometric questions. During his travels he climbed several mountains to measure the dependence of barometric pressure on height, noting at the same time the visual range, and became interested in further developing his early ideas on the transparency of the atmosphere:

> I did not foresee that one day I should climb the highest mountains of the earth, and make a very large number of observations which would make it possible for me to make a better determination of the logarithmic curve whose ordinates express the various densities of the atmosphere.[49]

Similarly, on board ship he noted the visibility of the sea floor and related it to variations in the transparency of sea water, to scattering of light through the water, and to surface reflections. In the last five years of his life, Bouguer returned to the subject of photometry. The resulting book detailing his researches was published shortly after his death.[50]

This second, and more extensive, work was not merely a revision of Bouguer's *Essai*. The first of its three parts dealt with 'means of finding the ratio between the intensities of two different lights'. He used his experimental techniques to evaluate, for example, how the brightness varied across the sky, and by how much 'the parts of the sun near its centre are more luminous than those which are near the edges of this body'. The second part was entirely new, and dealt with reflection from rough and polished surfaces. Bouguer examined, too, the scattering of light by the atmosphere, developing a theory of visual range to explain his South American observations. With his lucimètre he measured, and provided data for, most of the quantities he dealt with theoretically.

The eighteenth century polymath Johann Lambert (1728-1777) made his own study of illumination in 1760 at the age of 32. In a treatise on the subject, Lambert

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[48] P. Bouguer, *La Figure de la Terre. . . Avec une Relation Abrégée de ce Voyage* (Paris, 1749). He was later appointed Royal Professor of Hygrometry at the Hague.

[49] Bouguer, *op. cit.* [8], 209.

[50] *Ibid.* Bouguer's biographical details are from the translator's introduction and from *DSB* 2, 343-4.

coined the term *photometry* and discussed the need for a photometer, noting that the eye lacks an instrument analogous to a thermometer.[51] Lambert was familiar with at least two previous works: Bouguer's 1729 *Essai*, and the German translation of a text on optics by the Englishman Robert Smith.[52] According to Lambert, he had heard of, but not read, Bouguer's *Traité*, but refers to the *Essai* about a dozen times in his own book. The two investigators, however, employed very different approaches. Where Bouguer had favoured geometrical arguments and extensive experiments to confirm his ideas about nature, Lambert's work started from a foundation in analytical mathematics. According to W. E. K. Middleton, translator of Bouguer's *Traité*, to Lambert 'it was entirely fitting that all phenomena should at once be subjected to mathematical analysis. His instinct was to develop theory as far as possible, often on the basis of little experiment'.[53] Lambert's treatise covered an impressive array of topics, ranging from the intensity of direct, reflected and absorbed light; the photometry of the atmosphere; the illumination of planets; and, an investigation of colour and shadows. Unlike Bouguer's work, Lambert's was a formal treatise stressing mathematical derivations of light intensities based on the methods of geometry and the integral calculus.

The measurement of light provoked occasional interest in the second half of the eighteenth century as sources of artificial lighting were improved, partly to meet the demand for street lighting and production by the new industries. Manufacture often now continued beyond the hours of daylight. Particularly in France, the study of light and lighting was recognised as a worthy scientific activity. Antoine-Laurent Lavoisier was awarded a gold medal by the Académie Royale des Sciences for an

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[51] J. H. Lambert, *Photometria sive mensura et gradibus luminis, colorum et umbrae* (Augsburg, 1760). Abridged German transl. by E. Anding in *Ostwald's Klassiker der exakten Wissenschaften*, nos. 31, 32 and 33 (Leipzig, 1892).

[52] See Bouguer, *op. cit.* [8], Vol III, p. 57. R. Smith's *A compleat System of optiks* [Cambridge, 1738] was translated into German in 1755.

[53] *Ibid.*, p. ix. Middleton quotes a passage illustrating Lambert's preference for analysis rather than physical observation in his study of the hygrometer [from H. B. de Saussure, *Essais sur l'Hygrométrie* (Neuchâtel, 1783), p. ix]: 'Le célèbre Lambert. . . ce grand géometre, considérant ces objets sous son point de vue favori, semble s'être occupé du soin de tracer géometriquement la marche de l'hygromètre. . . plutôt que de l'hygromètre proprement dite'.

essay on the best method of lighting city streets.[54] Better oil burners and lamp chimneys date from this period: for example, Argand's centre-draught oil burner, which replaced the solid wick (1786), and the cylindrical lamp chimney (Quinquet, 1765) were touted as major achievements.[55] There is nevertheless little evidence that the writings of Bouguer and Lambert were applied during this time. Indeed, in a subject that each investigator seemed eager to reinvent, Bouguer's contributions were slighted not only in the eighteenth, but also in the nineteenth and twentieth centuries. One commentator wrote, 'there is very little evidence of any mathematical treatment of problems, or satisfactory definitions of the conceptions in Bouguer's work', but 'Lambert developed a system of conceptions. . . the principle of which is still in use unchanged today'.[56] It could be argued, however, that Bouguer's most lasting contribution was precisely in deciding which aspects of the subject required definitions, i.e. in discovering the limitations of the eye as a detector of 'absolute' intensity, and in limiting his experiments and discussions to those relating to a *ratio* of intensities.

A third extensive investigator of light intensity during the eighteenth century – but employing distinct methods and for different reasons – was the American Benjamin Thompson (1753-1814).[57] In 1794, Thompson devised a visual photometer for measuring light intensity, with which he measured the transmission of glass, the reflectance of mirrors and the relative efficiency of candles, lamps and oil burners.[58] Thompson's work is notable for its breadth, attention to experimental detail, and pervasively quantitative nature.

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[54]H. Buckley, 'Some eighteenth-century contributions to photometry and illuminating engineering', *Trans. Illum. Eng. Soc.* 9 (1944), 73-88.

[55]M. Schrøder, transl. by H. Shepherd, *The Argand Burner: its Origin and Development in France and England, 1780-1800* (Odense, 1969).

[56]H. A. E. Keitz, *Light Calculations and Measurements* (Eindhoven, 1955), 8.

[57]Count Rumford.

[58]B. Thompson, 'A method of measuring the comparative intensities of the light emitted by luminous bodies', *Phil. Trans. Roy. Soc.* 84 (1794), 67-82.

Where Bouguer had aimed at scientific answers to natural phenomena and Lambert sought mathematical justification, Thompson's work was grounded in meticulous experiment. His photometer, illustrated in Fig. 1, consisted of a sheet of white paper and a cylinder of wood fixed vertically a few inches from it. The two light sources to be compared were placed on moveable stands some 6 to 8 feet from the paper and from each other. The observer compared the shadows of the

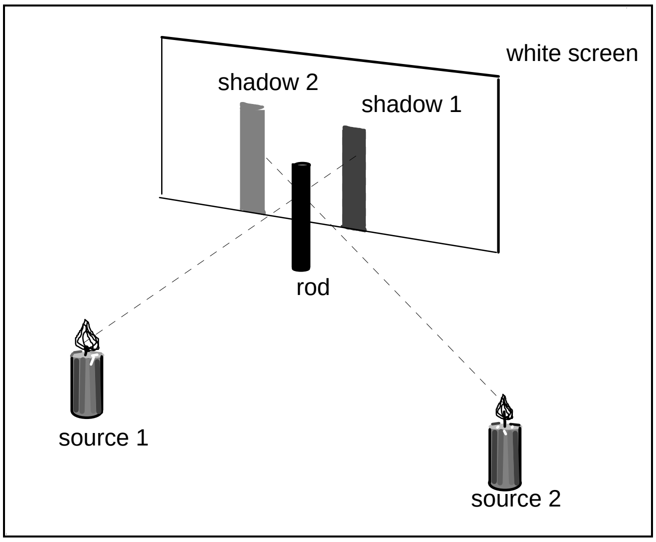

Fig. 1 Original version of Benjamin Thompson's photometer

cylinder cast by the two lights, and moved one or the other light further away until the densities of the shadows appeared to be exactly equal. Thompson concluded that the 'real intensities of the lights in question at their sources' were then 'to each other as the squares of the distances of the lights from the centre of the paper'.

Thompson used his devices in a series of carefully organised experiments covering a broad programme of research. He was much concerned with *efficiency*: measuring the illumination produced by various lamp fuels, he calculated their relative expense, observing the light emitted by an Argand lamp and by a wick lamp of common construction and finding that the Argand lamp used 15% less oil for the same illumination.[59] In studying the fluctuations of the light emitted by candles, he discovered a variation 'from 100 to 60' for a good quality candle, and as much as 100:16 for 'an ordinary tallow candle, of rather an inferior quality'. His observations

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[59]Thompson's general concern for practice and efficiency is also indicated by his development of the Rumford stove and work on the nature of heat.

guided the further development of his experimental method. He cautioned that 'in all cases it is absolutely necessary to take the greatest care that the lights compared be properly trimmed, and that they burn clear, and equally, otherwise the results of the experiments will be extremely irregular and inconclusive.'

Thompson's experiments investigated not only the brightness of light sources, but also the effect of common materials. He measured the loss of light through plates of different kinds of glass, providing a suggestion for commercial use:

> With a very thin clean pane of clear, white, or colourless window-glass, not ground, the loss of light, in 4 experiments, was .1321; .1218; .1218; .1213; and .1297; the mean .1263. When the experiment was made with this same pane of glass, a very little dirty, the loss of light was more than doubled. – Might not this apparatus be very usefully employed by the optician, to determine the degree of transparency of the glass he employs, and direct his choice in the provision of that important article in his trade?[60]

Mirrors, too, came under his scrutiny. Thompson noted that 'the mean of 5 experiments, made with an excellent mirror, gave for the loss of light .394; and hence it appears, that more than 1/3 part of the light, which falls on the best glass mirror that can be constructed, is lost in reflection.' Besides measuring the reflectance of various mirrors, he studied the effect of angle ('the difference of the angles of incidence at the surface of the mirror, within the limits employed, namely 45° to 85°, did not appear to affect, in any sensible degree, the results of the experiments').

Other experiments dealt with more fundamental questions. The first described in Thompson's paper concerned 'the resistance of the air to light'. He measured this 'transparency of air' by verifying the inverse-square law over the twenty-foot length of the photometer room. Thompson investigated the transparency of flame by comparing candles alternately in a line parallel and perpendicular to the screen (he found little difference, from which he decided that flame was transparent). Six years later Thompson used what he had learned in planning the lighting of the Royal Institution.

Thompson makes no mention of previous work, although his apparatus was similar to that described by Lambert some 34 years earlier. Nor does he make any reference, apart from the inverse-square law, to theoretical relationships; his

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[60]For a close 20th century parallel, see Chap. 8, ref [98].

photometry was strictly empirical, and directed towards answering immediate questions of illumination.

Despite his unique and potentially fruitful approach, Thompson's work, like that of Bouguer and Lambert, excited little interest. There appears to be no mention by his contemporaries either of his methods or results. Indeed, commenting on their work and the state of photometry as late as 1868, a French observer lamented:

> Nothing is more delicate, more difficult than the measurement of luminous intensities. In spite of all the progress achieved in the science of optics, we do not yet possess instruments which give this measurement with a precision comparable to those of other physical elements. . . we are struck that modern physicists have not thought at all about the subject.[61]

These eighteenth century examples of photometric research, although sparse, reveal qualities of the subject that characterised it throughout the period covered by this thesis. Firstly, differing *perceptions* of its feasibility and value are evident. On the one hand, characterised by Huyghens, Mairan and François-Marie, the measurement of light intensity was interpreted as a straightforward task susceptible to trivially simple methods and analysis. The eye was considered to be an unproblematic and reliable detector of brightness. On the other, epitomised by Bouguer, Lambert and Thompson, photometry was portrayed as a potentially misleading subject requiring careful experiment and analysis.[62] These contradictory perceptions, by practitioners seeking a quick answer to solve a larger problem on the one hand and investigators concerned with the foundations of the subject on the other, introduced confusion, dissatisfaction and lack of consensus. Secondly, the techniques of measurement were diverse, relying as they did upon sighting tubes, shadow-casting or glass-stacking. Thirdly, the style of engagement was highly variable. From the highly analytical approach of Lambert to the utilitarian fact-finding of Thomson, the motivations and methods of photometry were redefined by each investigator.

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[61]A. Guillemin, *Les Phénomènes de la Physique* (Paris, 1868), 272 (my translation).

[62]There was, of course, a third, implictly held, majority view, that photometry did not constitute a 'subject' worthy of 'study' at all.

Light as a law-abiding quantity

A view of light as an entity to be quantified was slow to become established. As discussed above, quantitative intensity relationships were proposed sporadically during the eighteenth century and earlier. Bouguer, Lambert and (later, in 1852) August Beer described eponymous intensity relationships.[63] Several of their predecessors had proposed their own laws, but with various unverified formulas.

The rather casual exposition of empirical intensity relationships without experimental confirmation was a mode of scientific discourse still operating in the early nineteenth century. For example, in an 1809 paper Étienne Malus, discoverer of polarisation by reflection, inferred the law of intensity as a function of polariser angle by a dubious method.[64] Knowing no means of accurately determining intensity, he never experimentally confirmed the relationship. Henry Fox Talbot later devised one, and in the process raised some of the issues later to become central to light measurement. Prompted by an ‘article in a foreign journal’, and seeking a method ‘to determine experimentally the intensity of a polarised ray’ he published in 1834 the investigations of photometry he had made nine years earlier:

> Photometry, or the measurement of the intensity of light, has been supposed to be liable to peculiar uncertainty. At least no instrument that has been proposed has met with general approval and adoption. I am persuaded, nevertheless, that light is capable of accurate measurement, and in various ways; and that the difficulties which stand in the way of obtaining a

[63]These state that the logarithm of the quantity of light received is inversely proportional to the thickness (Bouguer) and concentration (Beer) of an absorbing material, and to the cosine of the angle of incidence (Lambert) on the receiving surface.

[64]J. Z. Buchwald, *The Rise of the Wave Theory of Light* (Chicago, 1985), 45-8. Malus’ law relates the amount of light transmitted and reflected by two polarisers in series to the angle between polarisation axes. Malus observed qualitatively that the brightness of light refracted through a crystal of Iceland spar varied complementarily with that of the reflected component as the crystal was rotated. Assuming the total intensity to be conserved, he deduced that the reflected component was proportional to the cosine squared of the angle and that the refracted component was proportional to the sine squared.

> convenient and accurate instrument for photometrical purposes will ultimately be overcome.[65]

Talbot's claim that 'light is capable of accurate measurement' was to be repeatedly challenged until the end of the century. As he noted, there was no general agreement on the adequacy of photometry for any purpose. Talbot's method, related to persistence of vision, sought to redress the difficulties. Recalling that a glowing coal whirling around appears as a continuous circular ring,[66] he reasoned 'that *time* may be employed to measure the intensity of *light*'. To do so, a light source would repeatedly be eclipsed by a rapidly rotating wheel having one or more sectors cut away. An observer viewing the light would see an interrupted beam, but flickering too quickly to perceive. Talbot postulated that the apparent brightness should be proportional to the fraction of the cut-out diameter of the wheel. Thus, to avoid one of the problems he saw with photometry – that of obtaining a quantifiable reference intensity – Talbot appropriated a new physical effect. He saw this principle as being generally applicable to photometry, and indeed to many other forms of sensation:

> it offers a method (and perhaps the only possible one) of subjecting to numerical comparison some qualities of bodies which have never, I believe, been even attempted to be measured, such as the intensity of odours, &c; for this principle seems to have a general application. We may always find means of dividing the experiment into minute intervals of time, and we may cause that quality of the body which we wish to estimate the intensity of to act upon our senses or upon our instruments, only during a certain number of those intervals, but regularly and rapidly recurring in a stated order.[67]

Talbot thus broached another theme that was to dog the subject: that of relating perception to physical effect. His 'simple and natural' law was generally accepted by his successors and used as a reliable means of altering the intensity of light for photometric researches.[68] Talbot also extended his technique to colour research by

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[65] H. F. Talbot, 'Experiments on light', *Phil. Mag.* 5 (1834), 321-34; quotation p. 327-8.

[66] An observation noted by Isaac Newton, if not earlier.

[67] Talbot, *op. cit.*, 333-4.

[68] Although not the dominant one; see Fig. 8, Chapter 3. Talbot's law proved to fail when used to alter the exposure of photographic plates, especially when the flicker frequency was slow. See, for example, E. A. Baker, 'On the validity of Talbot's law for the photographic plate', *Proc. Opt. Convention* 1 (London, 1926), 238-44.

painting his rotating wheels with various proportions and tints. His methods failed to alter contemporary attitudes concerning the usefulness or applicability of photometry itself, though. Talbot's colour research with rotating discs was not picked up again for a half century.[69]

Talbot and a handful of predecessors concluded, then, that the brightness of light could be quantified to provide answers to both scientific and practical questions. The subject nevertheless failed to gain the direct attention of their scientific and engineering contemporaries. The clearest examples of subjects that might be expected to have embraced photometry, but did not, are photography and astronomy.

Photography: juggling variables

Developed from the 1830s, photography is seemingly tied closely to issues of light intensity. Apparently obvious questions – all quantitative – could be posed: how much light is needed to darken a photographic plate? How much are plates of different compositions darkened by the same amount of light? How much do different colours of light affect the results? How much does an optical filter reduce the intensity of transmission? Questions such as these reveal the gulf between the contexts of the mid nineteenth and twentieth centuries. Such questions were quite irrelevant to the concerns of the first practitioners, and were *not*, in fact, posed.[70]

Early photographers were concerned with the *effect* of light on the photographic plate rather than on its intensity. The two were not synonymous. A correctly exposed plate was the goal of the photographic method, and light intensity was merely one of the factors that affected the result. Instead of a fundamental interest in light, the photographer had an interest merely in its control as an exposing agent. The control of light was straightforward for most photographic work: the intensity could be varied over wide limits simply by altering the aperture of the camera lens.

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[69]By William Abney, whose contributions to the subject are treated at greater length in Chapter 4.

[70]Talbot himself, a seminal British innovator in photography and a photometric investigator, never combined the two studies.

Of greater importance to the photographer was exposure time, which was precisely controllable simply by shielding the plate from the scene to be photographed. Within broad limits, photographers discovered, exposure time and light intensity could be traded off.[71] Moreover, neither was critical in its effect on photographic density: a factor of two either way (amounting to a latitude of a minute or so) did not seriously affect picture quality. Thus exposure time, readily controllable to a few seconds for an exposure lasting several minutes, could be regulated to easily the necessary precision.

Another factor of more concern than light intensity was the sensitivity to light of various photographic processes. Great gains in sensitivity could be obtained by devoting attention to photo-chemistry. The first decades of photographic technology were thus dominated by the investigation of new light-sensitive materials, methods of development and 'fixing' processes.[72]

By contrast, light intensity was largely an uncontrollable factor in photography, as artificial lighting was generally too weak for exposure. Photographic processes of the period were sensitive mainly to ultraviolet and blue light, which was weakly emitted by flame and incandescent lamp sources. Intensity control was largely confined to designing photographic studios with skylights, large windows and adjustable mirrors to make best use of natural light.

Even when a gross error in exposure did occur, the later methods of plate development could compensate. Common practice with the relatively 'slow'

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[71]A photosensitive medium integrates light, changing its optical density in proportion to both the exposure time and intensity. In such a detector, either time or intensity can be used to control results. This relationship breaks down (the subsequently termed *reciprocity failure*) for extremes of intensity, exposure time or wavelength.

[72]This is illustrated by the great diversity of processes available by 1860. The earliest reported process of Niépce had relied upon the effect of light on the solubility to oil of a preparation of asphalt; the later *daguerreotype* employed a surface of silver, sensitised with iodine vapour, developed after exposure by mercury vapour, and 'fixed' by immersion in hot brine; the *calotype* process, by contrast, used paper soaked in silver salts, and was fixed by sodium iodide. Each successive process required less exposure time and preparation than did its predecessor. See, for example, C. Fabre, *Traité Encyclopédique de Photographie* 4 (Paris, 1890).

materials of the period was to hold the plate up to a dim lamp periodically during development and wash it free of chemicals when it was sufficiently dark. Writing in 1883, C. Ray Woods noted that:

> in studio work. . . there is a certain amount of uniformity; but in landscape photography the question becomes more complex. Quantity and quality of light, nature of subject and colour, atmospheric effects &c. – all these and more have to be considered. Arm yourselves with a photometer if you will, it is simply a matter of impossibility to correctly time the exposure, to give it, say, the theoretically exact quantity of light to produce the desired effect with a certain strength of developer.[73]

The use of an instrument to measure light intensity seemed pointless to the practical photographer, because there were simply too many extraneous factors influencing the exposure that could *not* be evaluated by a photometer. Light intensity was by no means the central factor in obtaining a good photograph. Wood's rough solution was to abandon any attempt to measure a 'theoretically exact quantity of light', and instead to expose the plate by about 'half as much again as the estimated exposure time' and then to develop very slowly in a bromide developer while observing the plate's density. One of his contemporaries noted that exposure was seldom a problem because both under- and over-exposed plates could be correctly developed by using 'strengthening' and 'restraining' developers, respectively.[74]

The occasional forays into light measurement by photographers were seldom appreciated by their contemporaries. As an evaluator of the 'Simonoff photometer' noted, 'the actinic or photographic energy is by no means always proportionate to its intensity', citing as an example the 'trebled' exposure required on days when the sky had a faint yellow caste. The second drawback, he noted, was that 'the eye of the observer may not always be in the same condition of sensitiveness to light; the iris being more or less expanded according to the brilliancy of the general illumination'.[75]

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[73]C. R. Woods, 'On latitude of exposure', *Photog. News* 27 (1883), 67-8.

[74]Anon., 'Latitude of exposure', *Photog. News* 27 (1883), 113-4.

[75]Anon., 'The Simonoff photometer', *Photog. News* 28 (1884), 610. This was a device in the form of a telescope incorporating an adjustable aperture wheel and graticule with scribed letters. The appropriate aperture, calibrated in terms of intensity, was selected to make the smaller letters illegible while the telescope was pointed at the light source of interest.

For early photographers, then, photometry was a solution in search of a problem. Photography until the late nineteenth century relied upon exposure time and processing conditions more than on control of light intensity to influence results. The problem of quantitative measurement of light was successfully avoided or recast in terms of other variables.

Astronomy: isolated forays

Nineteenth century astronomers undertook the measurement of light as diffidently as did photographers. While there were potentially a number of applications – determining stellar magnitudes, the brightness of variable stars, and eclipse phenomena, for example – none of these practices was central to the main concerns of astronomy at that time, and only isolated cases of interest can be found.

One such is William Herschel, who brought a quantitative point of view to astronomy as he was later to bring to the study of radiant heat.[76] His interest was provoked by reading a paper by John Michell in 1767 proposing to measure the distance of stars by their brightness.[77] Michell knew of Bouguer's earlier work in light measurement, and had devised a crude photometric method: enquiring how far away the sun would have to be to appear as bright as a typical star, he used Saturn as a reference. Saturn's brightness depended on the sun, and in opposition was as bright as a first-magnitude star. Its intermediate brightness, directly linked to the sun, made it a convenient photometric 'stepping stone' to relate solar and stellar brightness. By estimating a factor for the amount of sunlight Saturn received, he made a reasonable estimate of the distance of Sirius.[78] Theoretical calculations of planetary brightnesses had been published by Lambert, based on their distances, size and probable composition. Herschel carried this idea further over a period of years, by 1813 publishing a list of a series of reference stars for a range of magnitudes. To do so, he

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[76]On Herschel's novel astronomical style, see S. Schafer, 'Uranus and the establishment of Herschel's astronomy', *J. Hist. Astron.* 12 (1981), 11-26.

[77]J. Michell, 'An inquiry into the probable parallax, and magnitude of the fixed stars, from the quantity of light which they afford us, and the particular circumstances of their situation', *Phil. Trans. Roy. Soc.* (1767).

[78]M. A. Hoskin, *William Herschel and the Construction of the Heavens* (London, 1963).

observed pairs of stars through his telescope and reduced the intensity of the brighter one; from estimates of the amount of reduction needed to equalise the intensities, he inferred their relative brightness. Herschel related his scale of apparent intensity to one of actual distance. His simplistic relation between brightness and distance was attacked by several contemporaries, undoubtedly colouring their perceptions about the usefulness of photometric methods in astronomy.

Techniques of visual photometry

The cases cited above, and the accounts of the 1858 eclipse described in Chapter 1, illustrate the range of methods used to gauge or report light intensity through the nineteenth century. These techniques were frequently re-invented or recast into seemingly new forms. From a modern perspective the methods used fall into three categories of observation.

(a) Qualitative methods: intensity was related to a familiar value such as the brightness prevailing during various weather conditions. The report served simply to give an impression or paint a ‘mind picture’.

(b) Comparative methods: As Bouguer had observed, the human eye adapts to a large range of ambient lighting and so is intrinsically unsuitable for determining intensity. It can, however, be sensitive to temporal or spatial differences in intensity. Bouguer had recommended that brightnesses be evaluated by direct comparison of an unknown intensity with some known reference. The methods can be classified as either *extremum detection*, *thresholding* or *matching*. Each of these related methods needs a reference or standard of comparison.

In an *extremum* technique, the observer notes the point of maximum or minimum intensity by comparing the light with itself at a prior time or different position. This technique, used before intensity measurement proper, located the extrema of intensity. Augustin Fresnel, author of the first quantitative theory of diffraction which predicted particular angular positions for intensity minima, verified his predictions in the 1820s by an extremum technique.[79]

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[79]He appreciated that while the eye can determine the brightest point of a pattern with relative accuracy, determining the dimmest is even surer (the eye, once dark-

In a *thresholding* or *extinction* technique, the observer compares the intensity to a minimum detectable level. The intensity is reduced by some means until it is below the threshold of visual detection. The amount of reduction required is then a measure of the relative brightness. Airy's 'candle versus sun' technique for determining the intensity of the eclipsed sun adjusted the apparent intensity of the candle flame (the reference) by changing its distance relative to the sun until it disappeared. The text-reading method employed by Pritchard also had used thresholding as the comparison: he noted that distance at which text could be read to a certain standard of clarity. The reference in his case was therefore a definition of visual distinctness.[80] His method appears to have been shunned by serious investigators, however. It was subsequently recognised that visual thresholding is limited by eye accommodation, and depends on background lighting, the rate of change of intensity, and the characteristics of the observer. One attempt to obviate the effect of eye accommodation was to employ an aperture smaller than the smallest pupil diameter.[81]

Matching or *nulling* compares the intensity directly with a standard. The observer either adjusts the standard intensity until its difference from the unknown is 'nulled' or cancelled, or else uses several fixed standards for comparison. Bouguer, Lambert and Thompson all matched their subject to another known source such as a star, planet or standard candle.

(c) Physical methods: unlike visual methods, physical techniques relate intensity to some other physical effect. The actinic method used by Airy's assistant, James

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adapted with the iris fully dilated, cannot 'accommodate' any further to weak lighting).

[80]Bouguer, *op. cit.* [8], reported that the Swedish astronomer Celsius had used a similar method based on printed slips or black and white patterns. Geminiano Montanari, of the University of Bologna, published a comparable method in 1676; see Ariotti, *op. cit.*, 332, 338. The idea of reading text as a means of determining a threshold of intensity was current until at least the turn of the twentieth century; see, for example, ref [36] for an 1884 version. Such 'acuity' devices, based on the faculty for discriminating small details in patterns, were a class of photometers unique in that they did not rely on an observation of intensity.

[81]Heyde's Aktinophotometer of 1905; see D. B. Thomas, *The Science Museum Photography Collection* (London, 1969), 37, cat. no. 267.

Glaisher, relied on a photochemical effect: light intensity was determined by the amount of darkening of a photographic material. Similarly, the blackened-bulb thermometer indicated the intensity of irradiation by the length of its mercury column.

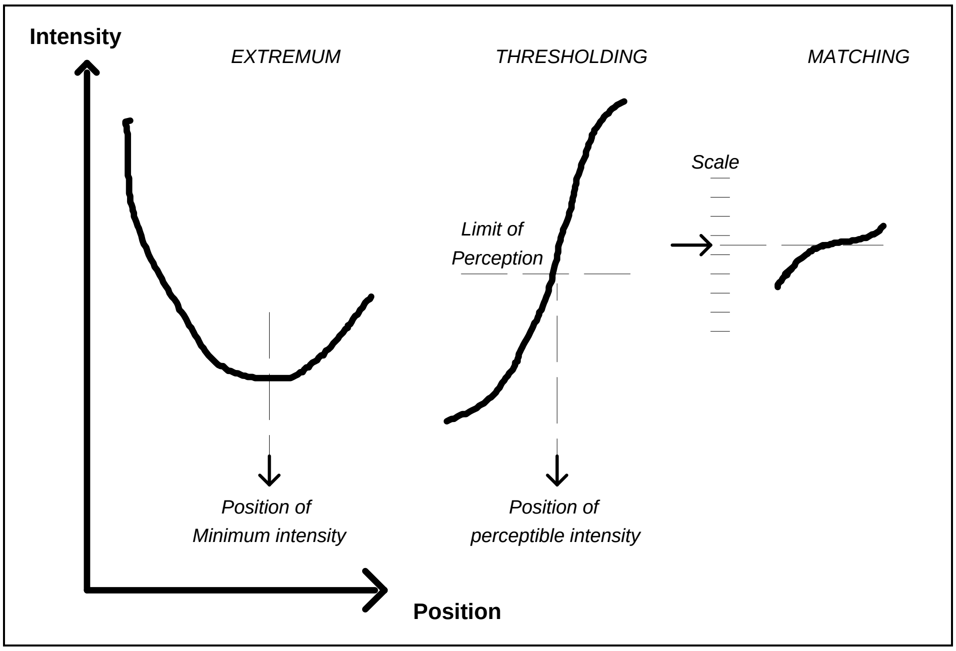

Fig. 2 Methods of visual photometry

These techniques were adequate to give a good estimate of the brightness of light sources or surfaces. Indeed, the capabilities of visual photometry exceeded what was demanded of it. There was little evolution of technique through the period; instead, old ideas were recycled in new combinations and for new purposes.

Observers thus had an assortment of methods at their disposal, ranging from the descriptive to the numerical. Until a consensus regarding the *value* of such observations was established, however, the methods remained diverse and unfocused. Scientific culture, as much as material technology, controlled the subject. The dual importance of these influences is revealed by two concurrent subjects related to intensity measurement which contrast sharply with the case of photometry. Researchers of *radiant heat* (a subject later to be strongly linked to the theoretical framework of energy physics) had long been performing careful quantitative experiments, while a collection of pragmatic investigators was attempting to describe and measure *colour* by quite different techniques.

Studies of radiant heat

The investigation of the intensity of radiant heat had an early history distinct from that of the brightness of light. Seventeenth-century investigators had observed the reflection and transmission of heat rays using their skin or thermometers as sensors, frequently making quantitative estimates. The French investigator Mariotte, for example, in 1682 noted that covering a concave mirror with a glass pane reduced the heating effect on a thermometer at the mirror focus by about one-fifth.[82] A flurry of activity in the late eighteenth century, using better thermometers, culminated in a series of experiments made by William Herschel in 1800.[83] Herschel, too, used thermometers as quantitative instruments, mapping the relative heat intensity provided by different colours. By equating the heat intensity to the change in scale reading of the thermometer upon illumination, Herschel was able to report, for example, that a sample of red glass stopped 692/1000 of the heat rays in the red part of the spectrum.[84] Others quickly extended his work, seeking to verify or disprove his claim that most heating occurred beyond the red end of the spectrum. In the process of investigating a plethora of discordant results, researchers studied the emissivity, absorptivity and transfer of heat between bodies.[85]

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[82] E. S. Cornell, 'Early studies in radiant heat', *Ann. Sci.*, 1 (1936), 217-25.

[83] E. S. Cornell, 'The radiant heat spectrum from Herschel to Melloni. I. the work of Herschel and his contemporaries', *Ann. Sci.* 3, (1938), 119-37.

[84] W. Herschel, 'Experiments on the refrangibility of the invisible rays of the sun', *Phil. Trans. Roy. Soc.* 90 (1800), 293.

[85] R. E. Olson. 'A note on Leslies' cube in the study of radiant heat', *Ann. Sci*, 25 (1969), 203.

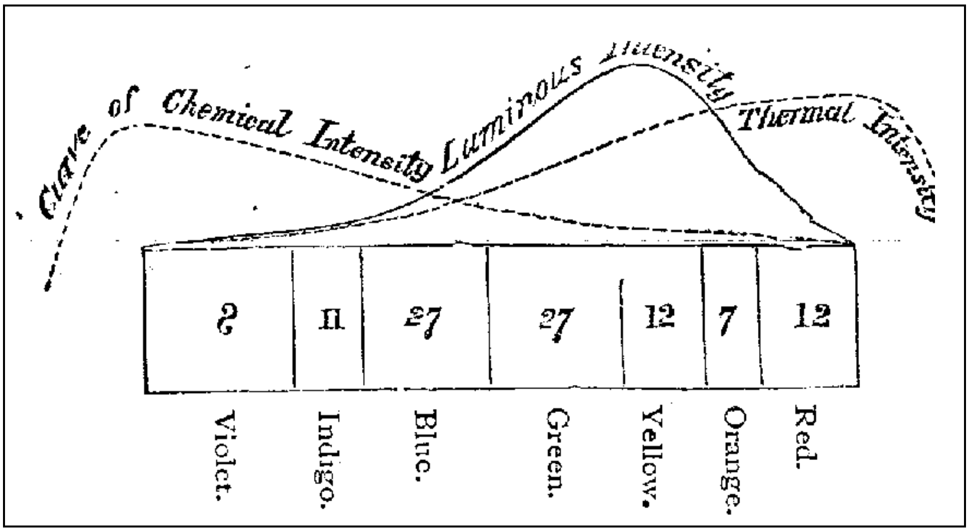

Fig. 3 The tripartite nature of radiation, from J. C. Buckmaster, *The Elements of Acoustics, Light and Heat* (London, 1875), p. 83.

Radiant heat remained a study distinct from photometry through the 1830s and 1840s, even though it was by then increasingly interpreted as a form of light.[86] By the 1850s, radiometry was linked to questions of heat transfer and energy, both 'hot' topics at the time.[87] As illustrated by Fig. 3, light and radiant heat had not completely merged in the scientific mind even by 1875. The effects of 'actinic', 'luminous' and 'thermal' radiation were seen as distinct.[88] As the three types of radiation acted preferentially on different types of detector (photographic materials, the eye and temperature-sensitive instruments, respectively), it was natural to employ the most sensitive for each, and to construct the subjects along observational lines.

Colour measurement

Just as the study of radiant heat was constituted as a distinct subject, colour was not closely linked to photometry among nineteenth century investigators. A brief sketch of the 'prehistory' of the subject of colour measurement will illustrate its

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[86]E. S. Cornell, 'The radiant heat spectrum from Herschel to Melloni. II. The work of Melloni and his contemporaries', *Ann. Sci.* 3 (1938), 402-16.

[87]S. G. Brush, 'The wave theory of heat: a forgotten stage in the transition from the caloric theory to thermodynamics', *BJHS* 5 (1970), 135-67.

[88]For a discussion of the effects of these radiations on selenium, see C. Hempstead, *Semiconductors 1833-1919: an historical study of selenium and some related materials* (PhD thesis, Durham Univ., 1977), 34-5.

separate and considerably later origins from the measurement of light intensity and radiant heat. During its rise in the nineteenth century, the subject was dominated by utilitarian need and pragmatic solutions. It was, moreover, of interest to distinctly separate communities comprising a schismatic collection of parties speaking mutually incomprehensible languages. Artists, industrialists and scientists had distinct ideas of colour measurement.

The nineteenth century preoccupation with colour measurement began with empirical means of using colour for systematic applications.[89] Mid-century efforts to characterise colour were frequently limited and qualitative. Artists, having more practical experience with the subject than most men of science, were the instigators of several systems.[90] Attempts to develop a 'notation' for colour generally centred upon expressing it as a combination of quantifiable characteristics. Besides the 'brightness' that was central to photometry, such attempts factored colour into the separable characteristics of 'hue' (or tint) and 'saturation' (or colour purity).[91] By treating these properties as co-ordinates, colours could be 'mapped' onto three-dimensional spaces. The Boston artist Albert Munsell, for example, devised a colour 'tree' to express all possible colours, intending it as a tool for industry and teaching.[92] The director of a French dye works developed another of the first such systems to characterise his

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

[90]David Ramsay Hay (1798-1866), for example, wrote on 'the numerical powers and proportions of colours and hues' in 1846. His rather arbitrary numerical descriptions intermingled with the flowery language of the artist: 'Blue. . . belongs more to the principle of darkness or shade. . . and is consequently the most retiring of the three. It is also of these elements the most cool and pleasing to the eye, associating, as it does, with the groundwork of the retina itself'. [D. R. Hay, *A Nomenclature of Colour* (London, 1846), 20-6]. Hay's method of quantifying colour was to assign rather arbitrarily proportions of 'light and darkness' with little reference to either experiment or theory. In this scheme, 'the phenomenon of colour seems to arise by a different mode of action', with yellow, for example, being embodied in 45 parts light and 15 parts darkness.

[91]M. Luckiesh, *Color and its Applications* (London, 1915).

[92]A. H. Munsell, *A Color Notation* (Boston, 1907). Munsell (1858-1918) lectured on colour harmony at the Massachusetts Normal Art School from 1890 to 1915. His colour system was influenced by the idea of a colour 'sphere' proposed by Nicholas Ogden Rood in *Modern Chromatics* (1879).

colours. His motive for developing a system of colour specification had initially been to investigate complaints from a customer about the fading of the colours of dyed fabrics.[93] Such systems proliferated by the turn of the century and fulfilled a practical need.[94] Numerical languages for colour met the requirements of commercial specification. Such systems were characterised by a certain rigidity of definition coupled with empirical details. The number of hues might be 10 (Munsell) or 36 (Ridgway) values; the number of grey levels, 6, 9 or 15; the number of colours defined, typically several hundred to a few thousand.

Besides matching fabrics, paints and flower colour, early efforts to characterise colour emphasised quantitative uses. Chemists coined the term *colorimetry* in the 1860s to refer to the determination of the quantity or concentration of a substance by the colour it imparted to a solution.[95] Although more complex than in the case of photometry, *matching* proved the most successful strategy, and various methods of colour matching were developed. One of the most successful of these was the 'Tintometer' invented by Joseph Lovibond, a former English brewer.[96] Based on the comparison of the coloured sample to a graded set of glass filters, the Tintometer found use in industries as diverse as steel production, water quality measurement and the valuing of flour. Such early applications had a strongly empirical basis. Although Lovibond spent several years investigating schemes of colour matching, he had no time for theorising. He confined himself to empirical experiment, which 'enabled the author to devote much of his time and energy to actual work, which would otherwise have been employed in profitless controversy'.[97]

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[93]M. E. Chevreul, *The Laws of Contrast and Colour* (London, 1858).

[94]For example, Robert Ridgway, Curator of Birds at the U.S. Museum, published his own *Nomenclature of Colors for Naturalists* in 1886. La Societé Française des Chrysanthémistes published its *Repertoire des couleurs* in 1905 to describe flowers, but the catalogue found widespread use in other domains

[95]The use of indicator solutions to infer content from colour change dates back at least to Gabriel Fallopius in 1564, and to Robert Boyle a century later. See A. Debus, 'Solution analyses prior to Robert Boyle', *Chymia* 8 (1962), 41-61, and 'Sir Thomas Browne and the study of colour indicators', *Ambix* 10 (1962), 30.

[96]J. W. Lovibond, *Measurement of Light and Colour Sensations* (London, 1897).

[97]J. W. Lovibond, *Light and Colour Theories* (London, 1915), 3.

Despite the efforts to render colour into numerical form, nineteenth century colorimetry made little attempt to *measure*; instead, it compared samples to arbitrarily defined colour standards. Such an activity was in no way quantitative. According to Norman Campbell's distinctions to be discussed in Chapter 3, 'the assignment of numerals to represent telephones or the articles of a salesman's catalogue is not measurement; nor – and here is a more definite representation of properties – the assignment of numerals to colours in a dyer's list'.[98]

Through the first half of the nineteenth century, then, a few isolated approaches tried to make sense of the brightness and colour of light and the nature of radiant heat. These three subjects, evaluated with distinctly different motives and techniques, were constructed along individualistic lines by a small number of investigators convinced of the value and feasibility of intensity measurement. Only studies of radiant heat – a subject perceived as being more akin to thermal physics than to optics – adopted early a quantitative approach. Colour seemed more amenable to a cataloguing or taxonomic strategy, a pragmatic solution to problems for which utilitarian considerations were paramount. Physical scientists for the most part ignored the measurement of visible intensity, or deferred it until other, more fruitful avenues for research had been explored. Neither early photographers nor astronomers – later proponents of a quantitative approach – made photometry an important component of their technical repertoire. Each had ample new phenomena to explore qualitatively before the more mundane work of quantitative measurement was needed to yield new results.

Light measurement was thus weakly pushed from two directions, simultaneously encouraging and discouraging its investigation. A handful of investigators developed *reasons* to measure light, and means to do so. But several factors limited their interest. The uncertain nature of the visual process, inherent complexities in visual photometry, dearth of theories to impel experimental verifications, and abundant problems to be investigated by non-quantitative methods, all kept photometry in the background until the second half of the nineteenth century.

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[98]N. R. Campbell, *An Account of the Principles of Measurement and Calculation* (London, 1928), 1. See also Chapter 3.

The 1858 eclipse occurred at the threshold of an emerging self-realisation for the subject.

Chapter 3

Towards Quantitative Measurement

A variety of processes – social, technological and scientific – transformed the brightness of light in the late nineteenth century from a concern of a few disparate individuals to a subject employed and studied by groups. This cultural transformation was accompanied by the growing identification of the subject as a part of physical science, steering it towards an increasingly quantitative expression. By the end of the century, however, photometry remained an undisciplined and fragmented study. This chapter discusses the changing perception of photometry among emerging communities of engineers and scientists, isolated by distinct backgrounds, expectations and goals. The fragmented status of this emerging subject is reflected in the heterogeneous case studies and issues discussed in this chapter.

Any discussion of quantitative measurement must begin with definitions. The physicist and philosopher of science Norman Campbell (1880-1949), who in 1928 cited photometry as a study still suffering from inadequate foundations, defined measurement as 'the assignment of numerals to present properties in accordance with scientific laws'.[99] He described quantification as being of three possible classes. In his first class, Campbell categorised values that are simply ordered or ranked according to a lesser-than, greater-than criterion. A scale of hardness is of this type.

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[99]Campbell's work spanned the philosophical and applied physics dimensions of light measurement, based on his experience successively at the Universities of Cambridge and Leeds, the National Physical Laboratory and the General Electric Company [*DSB* 3, 31-5]. See N. R. Campbell, 'The measurement of light', *Phil. Mag.* 44 (1922), 577-90, written when his research at GEC into photoelectric tubes was getting underway, and *An Account of the Principles of Measurement and Calculation* (London, 1928), written as commercial GEC phototubes were entering the market. In the latter (p. 45-6), he writes: 'Photometry lies outside the range of most physicists, but it offers very interesting problems in measurement. I have an especial interest in it, because I was wholly ignorant of it when I studied the principles of measurement, but have been led since to a close acquaintance with it. Accordingly it has provided a means of testing the principles to which the study of other fields has led.'

Values on such a scale can be compared and even equated, but it is not possible to quantify by *how much* various values differ.

In a second class of measurement, values may be ordered on a scale that has regular increments; the temperature scale is such a case. This scale still is not completely quantitative, because it does not support arithmetic operations. Temperatures, for example, cannot be added or subtracted.

'Countability' is the defining characteristic of the third, fully quantitative class of measurement.[100] In this type, the quantity has a direct relationship with the order of natural numbers. Campbell used the example of illumination to illustrate this class.[101]

Table 1 Classes of measurement as defined by N. R. Campbell

Class	Characteristics	Example
1	ranking, ordering	rock hardness scale
2	ordering with uniform scale	temperature
3	arithmetic operations	mass, length

Photometry, as employed by various practitioners through the nineteenth century, could fall into any one of these classes, although the first and second classes were the most common. The mere *ranking* provided by Class 1 measurement was a characteristic of stellar magnitudes in the first half of the century and earlier. Class 2 *ordering* of intensities typified usages such as early gas photometry. Class 3, involving wholly quantitative *measurement*, became common only in the last decade of the century, and then only with limited precision. Campbell himself noted that light intensity is a difficult case of his 'laws of measurement', because it is additive

[100]More precisely, the units follow the associative and distributive laws of arithmetic.

[101]He noted, however, that while 'the luminous flux from a lamp is a very important theoretical magnitude', in practice 'the fluxes from two lamps can never be added accurately because one lamp always absorbs some of the light from the other'. See *An Account of the Principles of Measurement and Calculation* (London, 1928), 44.

only for isolated wavelengths: if two colours are mixed, they do not in general add to a unique sum, because the results depend on the how the detector responds to different colours. Thus the hesitancy of researchers to adopt quantitative methods in late nineteenth century photometry can be attributed in part to the lack of assurance in the validity of this approach – in short, it did not appear to work well. As will be discussed in Chapter 7, the problem of colour and 'heterochromatic' photometry remained a sticking point through the inter-war period. Although it comprised an inchoate collection of techniques and usages in the mid nineteenth century, photometric practice was, a few decades later, striving for numerical expression.

Recurring themes

Interest in the quantitative measurement of light intensity increased in the second half of the nineteenth century owing to the creation of certain research problems, especially in the areas of astronomical and lighting photometry. This chapter discusses the scientific, social and technological factors responsible for the growth of a quantitative perspective up to the first years of the twentieth century. It chronicles the halting advance of light measurement by practitioners struggling to make sense of its complications, converting it from a little-used tool to a subject having commonly agreed basis. The subject was approached in different fashions by different communities of practitioners, and remained a discordant collection of techniques, apparatus and applications at the end of the century. Throughout the period of the precarious establishment of the subject, however, certain recurring themes can be distinguished.

With the increasing employment of photometry, practitioners discovered the limitations imposed by the human eye. Its reliance on visual observation proved a serious hindrance to the application of photometry because agreement between investigators was poor and because considerable labour was required for precise observations. Successive practitioners repeatedly faced the same questions. Was the eye reliable, and to what extent? Could apparatus be designed to improve its accuracy? Could another means of measuring light replace the eye entirely?

The 'human factors' in photometry were to crop up repeatedly. Intensity measurements could be perturbed not only by the vagaries of the eye, but also by those of the brain. Careful practitioners concluded that they could be misled by inadvertent prejudice, and that the matching of two lights by eye was prone to psychological bias. Probably the first investigator to voice this concern was Benjamin Thompson, who in 1794 had employed a double-blind method to avoid the problem. He adjusted the positions of light sources on his photometric bench by a hand-winch, giving notice to his assistant to

> observe, and silently write down, the distance of the lamp or candle, so that I did not even know what that distance was till the experiment was ended, and till it was too late to attempt to correct any supposed errors of my eyes by my wishes or expectations, had I been weak enough to have had a wish in a matter of this kind. I do not know that any predilection I might have had for any favourite theory would have been able to have operated so strongly upon my mind, . . . but this I know, that I was very glad to find means to avoid being *led into temptation*.[102]

Most practitioners ignored such niceties, and either accepted what they recognised as an imprecise measurement or carried on unaware of the potential systematic errors.

A second characteristic of the subject was its growth in popularity quite divorced from scientific and technological evolution. Growth – as evidenced by the number of papers published, number of practitioners, or number of photometric laboratories – was high in the latter decades of the century. This burgeoning popularity resulted from an increased perception of the utility of photometry. The elaboration of techniques and the evolution of a scientific basis, however, evinced no such trend: the practice of photometry, in relation to other sciences and technologies during the period, changed slowly. One reason for its slow development was the discovery, and repeated rediscovery, of practical difficulties in what appeared superficially to be a straightforward measurement technique. Among the several hundred photometric investigations published during the nineteenth century, few were directly concerned with such limitations.[103] With little serious exploration of their complexities, photometric methods were consequently abandoned as often as they were refined. Owing to the unexpected subtleties of visual observation, photometry was to gain a reputation as an imprecise or even impossible technique. Most

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[102]B. Thompson, *Phil. Trans. Roy. Soc.* 84 (1794), 362; author's italics.

[103]Of 564 publications on light measurement listed in the *Royal Society Catalogue of Scientific Papers 1800-1900*, 41% deal with uses of light measurement, 36% with photometer designs, 15% with units of light, and 8% with spectrophotometry, according to the Royal Society subject divisions. See Appendix I for a chronological break-down.

practitioners by the end of the century were engineers rather than scientists, and they relegated photometry to routine verifications rather than to continued development.

As was to be demonstrated repeatedly through the century, the reputed imprecision of photometry restricted the usages to which it was applied; in turn, the undemanding usages placed little pressure on practitioners to improve their technique. This circle of low expectations – imprecise results – poor reputation – low expectations thus relegated light measurement to the depths of the scientific toolbox.

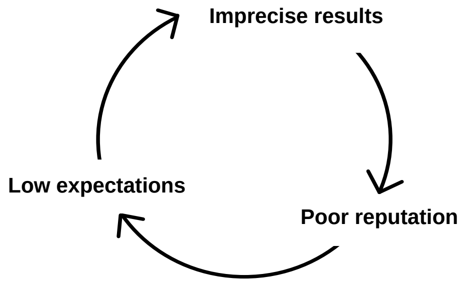

Fig. 4 Circle of development for photometry

A final theme to be illustrated in nineteenth century photometric practice is the scarcity of collaborative development. The *value* and *credibility* of photometry were to be repeatedly questioned and re-evaluated, and differed between communities, times and locales. The consignment of photometry to mundane applications, and its reputation as a straightforward if inaccurate technique, promoted its unenthusiastic usage by independent groups having little contact. This 'balkanization' of the subject inhibited change until the end of the century and relegated light measurement to a peripheral status in science.

Changes of approach after 1860

Chapter 2 described a period of 'prehistory' in light measurement, during which few connections existed between individual investigators. This situation began to change in the period 1850-80, however, when technological and cultural innovations combined to increase the influence and applicability of photometry. While the cause-and-effect relationships between these agents are difficult to map, I shall show how, in combination, they transformed the measurement of light intensity into a useful – if highly specialised – tool for diverse groups of scientists and engineers. The new networks grew first around newly valued *uses* of light measurement; that is, they had *cultural* nuclei. But the groups of practitioners remained disconnected; what had been studied by isolated individuals came to be studied by independent communities.

Astrophysics and the scientific measurement of light

A handful of astronomers, from the 1850s onward, nurtured the first durable interest in photometry. By the middle of the century, astronomers were becoming increasingly interested in extending their domain from that of merely astronomical time and position measurement. Among the new phenomena gaining attention, the brightnesses of stars and planets, until then relatively neglected, were amenable to systematic observation and classification. There had already been a number of published catalogues that included visual estimates of magnitude as an adjunct to positional co-ordinates.[104] In 1851, W. Dawes noted, though, the weaknesses of previous estimates:

> The differences among observers of great experience and celebrity are much greater than would probably be imagined by those who have not been led to examine the subject, and clearly show that widely different scales of magnitude have been adopted. . .[105]

According to Campbell's classification, stellar magnitudes at this time were of the first class, merely ranking values along an unreliable scale. To illustrate the poor precision of magnitude estimation, Dawes listed stars for which the magnitudes had been reported as anything from 5.3 to 8.5, discrepancies corresponding to differences of about eight times in estimated intensity.[106]

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[104]Stellar catalogues that included magnitude estimates appeared increasingly from the sixteenth century. In the seventeenth century, at least 7 such catalogues were published. Fewer astronomers held an interest in stellar magnitudes in the eighteenth and early nineteenth century, however. See K. Lundmark, 'Luminosities, colours, diameters, densities, masses of the stars', in G. Eberhard, A. Kohlschütter and H. Ludendorff (eds.), *Handbuch der Astrophysik* 1 (Berlin, 1932), 210-573, especially 224-73.

[105]W. R. Dawes, 'On a photometrical method of determining the magnitude of telescopic stars' , *Mon. Not. Roy. Astron. Soc.* 11 (1851), 187-90.

[106]Applying Pogson's scale of magnitude (described below). To improve the accuracy, he suggested using a threshold technique: a star would, he reasoned, be invisible to a telescope of a certain minimum aperture because the light collected

Some practitioners sought to improve the precision of their visual techniques, and to trace the experimental factors that limited it. More commonly, however, scientists intrigued by the possibilities of photometry applied the technique unaware of its difficulties. In 1878, Charles Zenger reported a method of measuring the relative intensity of planetary disks and satellites: he noted the time of disappearance of planetary features near twilight.[107] Zenger based his work on that of Bunsen (of prior fame in spectrum analysis) who had used a photographic technique to measure the background intensity of the sky versus the zenith distance of the sun, this serving as the reference for the threshold technique. Zenger reported no particular precautions concerning the sensitivity of the eye to differing levels of light, nor indeed any reference at all to the uncertainties of observation.

Surveys of the *Monthly Notices of the Royal Astronomical Society* for the latter half of the nineteenth century show that intensity measurement came to be adopted increasingly for special studies, and evolved towards a more quantitative and accepted technique in astronomical practice. In the same year as Zenger's work, for example, W. Christie made visual measurements of the disk of Venus, attempting to fit them to a theory of specular reflectance and diffusion by the planetary atmosphere.[108] Christie, appointed Chief Assistant at Greenwich in 1870 at the age of 25, was later to succeed Airy as Astronomer Royal. His interest in relating theory and experiment was new to late nineteenth century photometry. The emerging quantitative attitude was shared by the American Samuel Langley in the description of his new bolometer:

> I therefore tried to invent something more sensitive than the thermopile, which should be at the same time equally accurate, – which should, I mean, be essentially a "meter" and not merely an *indicator* of the presence of feeble

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would be insufficient to excite the retina of the observer. So, by 'stopping down' the objective lens, one could estimate the stellar magnitude. Dawes pointed out that this sort of photometry merely *ordered* intensities, and did not give them fixed numerical identities that could be added and subtracted. This was the very point reiterated by Campbell 75 years later.

[107]Ch. V. Zenger, 'On a new astrophotometrical method', *Mon. Not. Roy. Astron. Soc.* 38 (1878), 65-8.

[108]W. H. M. Christie, 'Notes on the specular reflexion of Venus', *Mon. Not. Roy. Astron. Soc.* 38 (1878), 108-9.

> radiation. The distinction is a radical one. It is not difficult to make an instrument far more sensitive to radiation than the present, if it is for use as an indicator only, but what the physicist wants, and what I have consumed nearly a year of experiment in trying to supply, is something more than an indicator, – a *measurer* of radiant energy.[109]

Obtaining an *indication* of light intensity was now seen as inferior to a *measurement*, in contrast to Airy's *notion/measure* equivalence of a quarter-century earlier. Measurement to Langley and his contemporaries was more than the mere ranking of magnitudes. Inherent in the idea was the ability to reproduce observations, and to relate them in a precise, repeatable way to other physical quantities – a strategy to extract more from observations. This linking with other forms of measurement was a key to promoting the quantification of light. The change in emphasis was reflected in the birth of a new subject of study: astronomy was joined by 'astrophysics'.[110] A typical article of the newly renamed journal *Astronomy and Astrophysics* in 1892 (the year of Airy's death) was on the 'Distribution of energy in stellar spectra'.[111] This work paralleled similar studies of the sun made by Herschel nearly a century earlier, but now appropriated it for the use of astronomers. The new community of astrophysicists saw clear reasons for measuring the intensity of starlight:

> The problems of stellar photometry are closely connected with many cosmic questions, primarily with the light changes of variable stars; but they have an equally important bearing on the questions of stellar distribution and evolution. It has been said by good authorities that it is of more importance to measure the light than the place of a star, and if one considers merely the astonishing number of variable stars now being discovered, it will be admitted that the importance of stellar photometry can scarcely be overestimated.[112]

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[109]S. P. Langley, 'Researches on solar heat', *Proc. Amer. Acad. Arts Sci.* 16 (1881), 432-436; see also 'The bolometer,' *Nature* 25 (1881), 14-6. For biographical details, see C. D. Walcott, 'Samuel Pierpont Langley', *Biog. Mem. Nat. Acad. Sci.* 7 (1912), 245-68. The bolometer, which measures the change in temperature caused by incident radiation, is more sensitive than the thermocouple, which generates a voltage related to temperature difference, and the thermopile, consisting of thermocouples in series.

[110]H. Plotkin, 'Edward C. Pickering, the Henry Draper Memorial, and the beginnings of astrophysics in America', *Ann. Sci.* 35 (1978), 365-77.

[111]E. C. Pickering, *Astron. & Astrophys.* 11 (1892) 22-5.

[112]J. A. Parkhurst, *Researches in Stellar Photometry* (Washington, D.C., 1906), 1.

Having created a *need* to measure light, then, what strategies did these practitioners use to tame this difficult subject? One of the 'good authorities' mentioned by Parkhurst was probably the astronomer Edward C. Pickering (1846-1919), who provided Parkhurst with his instruments. Pickering, professor of physics at the Massachusetts Institute of Technology and director of the Harvard College Observatory, was then at the centre of developments in astronomical photometry and spectroscopy, and had been important in influencing the acceptance of these subjects by astronomers.[113] He was not, though, solely responsible for the growth of this research area. Stellar photometry, the first concerted usage of light measurement for scientific applications, had begun at Harvard with its first director, William C. Bond (1789-1859). In 1850, Bond applied photographic methods to the making of photometric measurements of stars.[114] His work attracted other astronomers to photometric observations soon afterwards. N. R. Pogson, in 1856, employed a visual photometer to evaluate starlight, and found that Hipparchus' scale of magnitude gave approximately a factor of 100 between the intensity of first and sixth magnitude stars. To create a scale of uniform increments (moving stellar photometry from Campbell's 'class 1' to 'class 2' measurement), he therefore proposed the definition of a magnitude change of 1 as a change in intensity of $100^{1/5}$ (approximately 2.5 times). The definition was probably the first numerical interval to be applied to intensity measurement. It proved even more useful than technical developments because it promoted the sharing of observations between subsequent astronomers. At Oxford, Charles Pritchard (1808-1893) used a wedge photometer to measure the magnitudes of stars visible to the naked eye at up to 100° from the north pole.[115] His catalogue, the *Uranometria nova Oxoniensis* published in 1866, agreed 'quite well' with Bond's

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[113] S. I. Bailey, 'Edward Charles Pickering', *Biog. Mem. Nat. Acad. Sci.* 15 (1934), 169-92.

[114] W. C. Bond, *Ann. Harvard Coll. Observ.* 1 (1850), 149.

[115] S. P. Langley, C. A. Young and E. C. Pickering, 'Pritchard's wedge photometer', *Mem. Am. Acad. Arts. Sci.* 11 (1886). As with many photometric innovations, the origins of wedges of graded transparency are unknown. The use of a wedge was certainly described by L. A. J. Quetelet in 1833, and by R. Sabine for photographic use in 1882.

work, 'providing a generally acceptable magnitude sequence for the brighter stars'.[116] An assistant at Harvard, Charles S. Peirce (1839-1914), published the work he carried out between 1872 and 1875 as *Photometric Researches*.[117] Such comparisons and collaborations signalled the beginning of the social phase of astronomical photometry. Indeed, these photometric atlases promoted networks of individuals and institutions just as they created relationships between stellar objects.

Sharing Bond's conviction of the usefulness of such observations, and building upon the work already done at Harvard College Observatory, his successor Edward Pickering initiated an extensive programme of stellar photometry at Harvard College Observatory when he became director in 1877. Pickering introduced several innovations to convert photometry from a volatile to a sound subject. The first of these was in promulgating a standard. By adopting Pogson's scale of magnitude, and choosing Polaris as the reference star against which all others would be compared, he defined a photometric scale that other workers found straightforward to accept. Secondly, Pickering established a reliable technique. Working with the firm of Alvan Clark & Sons, he devised new types of visual photometer adapted for telescopic use. By means of adjustable mirrors, his 'meridian photometers' combined an image of Polaris with the target star as it crossed the meridian.[118]

Pickering's third tool of persuasion was sheer volume of data. To command attention, the new photometric systems had to map a representative number of stars. The first *Harvard Photometry*, published in 1884, catalogued some 4,000 stars. On its completion, Pickering immediately promoted a more extensive stellar survey. Between 1889 and 1891, Solon I. Bailey took the equipment to South America to

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[116]*DSB* 11, 155-6. The term 'uranometry' refers to the measurement of celestial objects, deriving from the Greek *ouranos* (heavens). Catalogues based on photographic photometry sometimes were entitled 'actinometries'.

[117]Pickering's brother William Henry (1858-1938), also at Harvard, published a work with the same title in 1880.

[118]Polaris, the north star, was useful in that it was relatively bright and maintained a fixed position in the sky, thereby making possible its observation during an entire night. As the two stars had different elevations, Pickering found it necessary to make corrections for the effect of atmospheric attenuation, a factor which he determined empirically.

catalogue the stars of the southern hemisphere. By 1908, Pickering and his co-workers had extended the work tenfold, cataloguing 45,000 stars in their *Revised Harvard Photometry*,[119] Pickering alone recording some 1.4 million observations.[120] John Parkhurst, the final recipient and user of Pickering's instruments from the opening of Yerkes Observatory in Chicago in 1897, carried on through the 1920s, having by then switched to photographic photometry.[121] By defining an observational method, publicising his data, and training and supporting energetic acolytes, Pickering thereby legitimated astronomical photometry and enlisted the support of the astronomical community.

Besides this American concentration of photometric research, most nineteenth century astronomical photometry took place in Germany. As in America, an observing community spread from an observatory where the practice of photometry was stabilised. Johann Zöllner (1834-1882) became interested in stellar photometry as a student, and defended perhaps the first PhD dissertation on photometric research in 1859.[122] Zöllner marshalled technique and training to extend the influence of stellar photometry as Pickering was later to do. His 'astrophotometer', which incorporated a petroleum-burning reference lamp, was adopted by other German observers.[123] Established in 1877, the Potsdam Observatory became a centre for

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[119]Published as volumes 50 and 54 of *Ann. Harvard Coll. Observ.* (Harvard, 1908).

[120]J. B. Hearnshaw, *The Analysis of Starlight: One Hundred and Fifty Years of Astronomical Spectroscopy* (Cambridge, 1986), Section 5.1.

[121]J. A. Parkhurst and A. H. Farnsworth, 'Methods used in stellar photographic photometry at the Yerkes Observatory between 1914 and 1924', *Astrophys. J.* 62 (1925), 179-90.

[122]J. Zöllner, *Photometrische Untersuchungen, insbesondere über die Lichtenwickelung galvanisch glühender Plantindrähte* (PhD thesis, 1859). This was followed by a treatise on stellar photometry, *Photometrische Studien mit besonderer Rücksicht auf die physische Beschaffenheit der Himmelskörper* (Leipzig, 1865). For further biographical details, see *DSB* 14, 627-30.

[123]Pickering, too, spent two years experimenting with variants of Zöllner's instrument before devising his meridian photometer.

photometric observations and produced a line of researchers.[124] Zöllner's student, Hermann Carl Vogel (1834-98) while working at observatories in Kiel and Potsdam from 1870 undertook an extensive programme of stellar classification using spectroscopic and photographic techniques. Gustav Müller, in his turn, gained an interest in photometry while working as an assistant to Vogel at Potsdam. Between 1886 and 1906, he planned and carried out an extensive programme of stellar photometry. Adopting Pogson's scale of magnitude as Pickering had done, Müller's *Photometrische Durchmusterung des nördlichen Himmels* catalogued over 14,000 stars.[125] The measurement precision of this generation of catalogues was considerably better than their predecessors.[126]

The isolated but extensive and respected work of the Harvard College and Potsdam observing communities influenced the following generation of astronomers. Ralph Sampson, for example, (1866-1939), later Astronomer Royal of Scotland, was to specialise in photoelectric photometric studies through the inter-war period because of their influence. According to one chronicler, the 'advent of Harvard photometric eclipse observations of satellites of Jupiter stimulated him to re-examine previous observations' and instigated his interest.[127]

The success of photometric and photographic methods in astronomy led the astrophysicists to more difficult but vastly more fruitful techniques. By the turn of the century, *spectro*photometric observations were being made. As early as 1899, Karl Schwarzschild (1873-1916), then an observatory assistant in Vienna, developed techniques for combining spectroscopy with photographic photometry. These allowed the relative intensity of a star to be mapped as a function of wavelength, by

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[124]For a discussion of the early Potsdam and Harvard observatories, see K. Krisciunas, *Astronomical Centers of the World* (Cambridge, 1988).

[125]*DSB* 9, 563-4.

[126]Typically 0.1 to 0.2 magnitude, or about 10% to 25%. See Lundmark, *op. cit.*, for detailed inter-comparisons of stellar catalogues listing magnitudes measured by visual photometry.

[127]*DSB* 12, 95-6.

applying the photometric method successively to narrow bands of wavelengths.[128] From this colour information, experimentalists could classify stars by type, and theorists were able to estimate temperature.[129] Stellar classification, based on spectral lines and photometrically determined temperatures, became a major activity in astrophysics.[130]

The isolation of the observing communities diminished as the number of practitioners grew. Hans Rosenberg (1879-1940), for example, began working with Schwarzchild around 1907, where he analysed spectrograms using a Hartmann microphotometer.[131] In the following decade Rosenberg worked at Yerkes Observatory, where Parkhurst had started a photometry programme in 1897 with the help of Pickering. Starting from a handful of centres in the second half of the nineteenth century, astronomical photometry had become a co-operative international network before the Second World War.[132]

By the beginning of the twentieth century, then, astronomical photometry was an established technique employed by a growing community of astrophysicists. Their *motivations* had been transformed during this period, however. Where Herschel's enthusiasm for photometry was unshared by his contemporaries, and Bond's interest in the 1850s had been provoked by a desire to catalogue more fully the heavens, the

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[128]A spectrometer dispersed both the starlight and a reference source, typically a flame, electric lamp or another nearby star of known characteristics. A region of the resulting spectra, located one above the other, was isolated using a slit, and the intensity of the reference band was adjusted to match the subject star.

[129]The relative intensity as a function of wavelength was related to stellar temperature by blackbody formulae.

[130]See Hearnshaw *op. cit.* 208 and 220-2.

[131]He was subsequently one of the first to apply photoelectric methods to astronomical observations, and developed recording photometers in the 1920s. The technology of astronomical photometry is discussed in Chapter 6.

[132]Astronomical photometry developed a larger academic component than did other versions, as evidenced by doctoral dissertations, e.g. that of Zöllner (footnote [24]), A. L. Bennett, *A Photometric Investigation of the Brightness of 59 Areas of the Moon* (PhD thesis, Princeton Univ., 1928) and J. S. Hall, *Photo-Electric Photometry in the Infra-Red with the Loomis Telescope* (PhD thesis, Yale Univ., 1933). See D. Hoffleit, *Astronomy at Yale* (New Haven, 1992), 131-40.

growth of the stellar photometry was due in large part to successful lobbying by a few individuals. The demonstration of the feasibility of the technique and the supply of voluminous data from the Harvard and Potsdam observatories, owing to the energetic programmes of Pickering, Zöllner and their followers, served to render the measurements trustworthy. From the 1880s, however, the additional information provided by spectroscopy became a major incentive in astronomers' adoption of photometric techniques.

Spectroscopy

While serving eventually as an impetus to astrophysics, the study of spectroscopy was at first only peripherally concerned with light intensity.[133] Quantitative measurement became increasingly attractive to its practitioners, however. Following Bunsen's and Kirchoff's investigations in the late 1850s, investigators began to use spectrum analysis to infer chemical composition. The presence or absence of particular spectral lines was originally the sole criterion of analysis. Spectral lines were initially classified by their relative positions in the spectrum (e.g. Fraunhofer's alphabetic ordering of prominent solar lines), followed somewhat later by wavelength values. Towards the end of the nineteenth century, astronomical spectroscopists began to describe certain spectral lines by their appearance. They noted, for example, that particular lines always appeared sharp, or diffuse, and that certain lines were always characteristic of a substance. Semi-quantitative descriptions such as *sharp*, *principal*, *fine* and *diffuse* gained currency.[134]

Initial interest centred upon the *identification* of small quantities of material rather than on determining its quantity. In popular lectures given in 1869, J. Norman

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[133]General histories of emission spectroscopy are given by W. McGucken, *Nineteenth Century Spectroscopy: Development of the Understanding of Spectra 1802-1897* (Baltimore, 1969), and H. Dingle, 'A hundred years of spectroscopy', *BJHS* 1 (1963), 199-216.

[134]See, for example, H. F. Newall, *The Spectroscope and its Work* (London, 1910), which describes 'Principal' and 'Subordinate' spectral lines, the latter being 'fainter but sharper'. As in stellar photometry earlier in the century, spectroscopists used a rough estimate of intensity (usually into three or four ranks) to label lines.

Lockyer (1836-1920) emphasised spectroscopy's potential for detection and discovery, a role seemingly divorced from quantification:

> not only are we able to differentiate between different bodies, but the most minute quantities of substances can be determined by this method of research. . . for instance, Kirchoff and Bunsen have calculated that the 18-millionth part of a grain can be determined by the spectroscope in the case of sodium.[135]

The example of ubiquitous sodium, and the discovery of new elements, was to reappear in many popular accounts of spectroscopy.[136]

For laboratory spectrum analysis, the neglect of intensity measurements by experimenters was in part a consequence of the instability of the light source: the flames commonly used to heat specimens varied in intensity and temperature, and thus were far from stable subjects. Also, the intensities of different spectral lines from a single source could differ by 1000:1 or even 10^6:1, making photographic methods ill-suited owing to their limited dynamic range.[137]

Interest in this minor subject grew as new spectroscopic phenomena emerged.[138] Technology and organisation also shared significant responsibility for a growth in popularity. From 1870, the availability of dry gelatine photographic plates made photographic spectroscopy more practical. Units of wavelength had been

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[135] J. N. Lockyer, *The Spectroscope and its Applications* (London, 1873), 51.

[136] Lockyer cited the recent examples, too, of the discovery of the elements of caesium and rubidium in spring water by Bunsen (1860), of thallium by Crookes, and of indium by Reich and Richter in Germany. Despite this emphasis on mere *detection*, there was some interest in the potential for *quantifying* materials. A Mr. Sorby, writing the same year, noted that he could measure the age of wine by the intensity of a particular spectral absorbance band. Using a 'microscope spectroscope' to examine vials of wine, he observed that 'the difference for each year is at first so considerable that wines of different vintages could easily be distinguished' [*Chem. News*, Dec 17, 1869, p. 295].

[137] Single-exposure photography was able to measure intensity ranges of scarcely 100:1, and this only when carefully calibrated.

[138] For example, G. G. Stokes and others explored the ultraviolet spectrum in the early 1860s when quartz was found to make a suitably transparent prism. In 1865, Balmer discovered a simple numerical fit for part of the spectrum of hydrogen, supporting the contention that spectroscopy had a mathematical basis. New physical effects were discovered, such as the spectral perturbations caused by magnetic fields (Zeeman, 1896).

standardised by 1890, promoting the comparison of results and strengthening the links of the social network. The new techniques had an immense scientific pay-off. Spectroscopy (both visual and photographic) was being used to infer the velocity, temperature and composition of stars and planets, and to probe new phenomena.[139] The potential of the new research programmes convinced practising spectroscopists of the need for further development of intensity measurement.

Standards, gas and electrotechnical photometry

Photometry had hitherto been an intensely personal affair. The apparatus had to be designed and calibrated by each investigator, the observations were performed in a light-tight room or at a telescope eyepiece, and the results relied solely on the evidence of his eyes. Communication of results demanded, however, that intensity calibrations be regularised. The socialisation of the subject relied upon standards.[140]

Such intensity standards were not trivial to generate. The astronomer John Parkhurst, for instance, calibrated his graduated wedge for stellar photometry using two methods: first, by making measurements 'of standard stars whose magnitudes have been well fixed'; and secondly, 'by measurements of an artificial star whose light can be reduced by a known amount either by (a) polarisation, (b) a revolving wheel, or (c) reduced apertures by stationary diaphragms'.[141] The comparison of individual instruments was tedious: Parkhurst reported making 2700 measurements on standard Pleiades stars, 3000 readings for a comparison with a Zöllner photometer, and 500 readings for comparison with a 'wheel' (Talbot) photometer. Even with such careful photometric methods, though, astronomers felt compelled to emphasise that

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[139]See, for example, H. C. Vogel, 'On the spectrographic method of determining the velocity of stars in the line of sight', *Astron. & Astrophys.* 11 (1892), 203-7. The precision of Vogel's spectrographic methods far exceeded that available by visual observations. For a further discussion of Vogel's work, see Hearnshaw, *op. cit.*, 77-89.

[140]The form the standard took depended, in turn, on cultural factors. For the electrical case, see B. J. Hunt, 'The ohm is where the art is: British telegraph engineers and the development of electrical standards', *Osiris* 9 (1994), 48-63.

[141]Parkhurst, *op. cit.*, 8. The 'artificial star' was a lamp located behind a pinhole aperture, and collimated by a lens so as to appear to be located at infinity.

they still ‘found it by no means easy to get good concordant observations’.[142] The brightness of fluctuating light sources such as twinkling stars was difficult to measure by relatively slow visual or photographic observations. Measurements were further hampered by changing sky conditions.

The use of ‘standard stars’ ‘well fixed’ by other observers can be seen as Parkhurst’s attempt to enrol an ill-defined community to support his measurements. Stellar catalogues served a social role in forming that community. But the difficulty in obtaining ‘good concordant observations’ illustrates the fragility of this grouping of practitioners at the mercy of their technology. While such time-consuming methods of characterisation were practical for some scientific work, they were wholly unacceptable for industrial problems. If photometry was to be accepted widely, reasoned some practitioners, generally available standards of light measurement and intensity were required.

Utilitarian connections

Light standards were impelled by utilitarian requirements, and photometry gained new supporters through its connection with questions of illumination. Intensity standards in commerce and industry became widely sought and employed during the second half of the nineteenth century, when the regulation of gas lighting provided an incentive for development. The quest for a standard, in its turn, supported the growth of new communities recruited to maintain and employ it.

Until the late eighteenth century, open oil lamps and candles had undergone little active development. The Argand lamp of 1786 demonstrated the value of thoughtful design, and promised a more stable light standard. The Carcel, developed in France in 1800, was another successful oil lamp containing a clock-work pump for supplying oil to the wick.[143] In 1860, its burner and chimney dimensions were standardised for use as a reference for testing the illuminating power of Paris gas.

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[142]G. Liveing & J. Dewar, ‘On the influence of pressure on the spectra of flames’, *Astron. & Astrophys.* 11 (1892), 215-21.

[143]E. Alglave & J. Boulard, *La Lumière Électrique: son Histoire, sa Production et son Emploi*, (Paris, 1882), 8-9, and A. Palaz, *Treatise on Industrial Photometry*, transl. by G. W. & M. R. Patterson (N.Y., 1894), 111-8.

The English standard, the *Parliamentary candle*, was similarly defined for the same reason. Gas testing, the first routine use of photometry, gave the technique a legal and economic dimension.

The illuminating gas industry, originating in England in the early decades of the century, provided the dominant source of domestic and public lighting in most cities within two decades.[144] The first company in London was set up in 1810, and the number of companies supplying gas in the capital reached 13 before falling to three in the 1880s as a result of mergers. The Metropolitan Board of Works (MBW) was given extensive powers to supervise the industry in the early 1860s when the number of companies proliferated. Following public concern about the accuracy of gas metering and the purity of gas, Parliament passed legislation to give supervisory powers to magistrates. When this measure proved ineffective, the Metropolitan Board of Works was given responsibility.[145] The first gas examiner was appointed in 1869, followed by four more a year later. A unified department concerned with the legislation and regulation of the gas supply grew out of the MBW.[146]

The gas standards to be verified centred on illuminating power and purity.[147] Groups of gas examiners were responsible for particular areas of London, with an inspector responsible for one metering house. By 1889 some 22 locations were specified.[148] The legal requirements created a new community of photometrists. These first salaried light-measurers were highly trained with respect to the other

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[144] T. I. Williams, *A History of the British Gas Industry* (Oxford, 1983). For an introductory history of gas lighting, see W. Schivelbusch, *Disenchanted Night: The Industrialisation of Light in the 19th Century*, transl. by A. Davis (Oxford, 1986).

[145] G. C. Clifton, *Professionalism, Patronage and Public Service in Victorian London: the Staff of the Metropolitan Board of Works 1856-1889* (London, 1992), 32.

[146] *Ibid*., 42-3. The MBW promoted bills in the 1860s and 70s to allow it to supply gas or to purchase gas companies. These bills failed, but led to enforcement of stricter regulations of the gas companies by the MBW.

[147] See J. Abady, *Gas Analyst's Manual* (London, 1902), in which the first chapters are devoted to photometric techniques.

[148] W. J. Dibdin, *Practical Photometry: a Guide to the Study of the Measurement of Light* (London, 1889), 181-2.

administrative staff: half had studied at a university or equivalent, compared with 6 per cent of the other departments of the MBW, and all employed photometric and chemical analysis in their work.[149] It is thus safe to say that the major users and adapters of photometric equipment, and the most numerous photometrists, were the gas examiners of London and certain other gas-supplied cities between at least 1860 and 1880.

The scientific practices of the staff, and physical standards of illumination, were set by a body of experts known as the Metropolitan Gas Referees. The Superintending Gas Examiner, William Joseph Dibdin (1850-1925), Chemist to the MBW in the late 1880s, thoroughly investigated the available photometric methods and published one of the first widely available books summarising the subject.[150] Observing that 'the present chaotic condition of the Photometer itself is a fruitful source of much uncertainty', and attempting to reassure the 'newly-appointed and possibly somewhat nervously constituted Gas Examiner', he sought to give 'a full narration of the various systems now before the public'.[151] Not only did Dibdin strive to provide practical answers to utilitarian problems of gas testing; he also prescribed procedures for measuring electric lights, and made an examination of stellar photometry. By providing a comprehensive text, recommending standardised methods and training scientific staff, the Metropolitan Gas Referees thus became the *de facto* arbiters of photometric standards in England.[152]

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[149] *Ibid.*, 77.

[150] *Ibid.* Dibdin became better known from the 1890s as a pioneer of biological sewage treatment. See C. Hamlin, *A Science of Impurity: Water Analysis in Nineteenth Century Britain* (Berkeley, 1990), 283-4.

[151] Dibdin, *op. cit.*, v-vi. The book provides several examples of the legal disputes surrounding the intensity of gas lighting in Victorian London, and of the variety of hardware employed to resolve them.

[152] The illuminating gas industry, on its part, consolidated expertise in photometry and other technical subjects by establishing the British Association of Gas Managers in 1863. It aimed at 'progress through the enlarged intelligence of its members to be brought about by the free interchange of opinion and experience' [R. A. Buchanan, *The Engineers: a history of the engineering profession in Britain 1750-1914* (London, 1989), 95-6].

One of the first tasks of the Referees was to seek improved intensity standards. The accuracy of the Parliamentary Candle, the first standard defined by the Referees, was poor: although intended to burn 120 grains of spermaceti per hour, initially only the candle weight (one-sixth of a pound) was specified. By 1871 the specification had been elaborated to provide permissible limits (114 - 126 grams/hour, or ± 5%) and a description for the manufacture that included wick and wax characteristics.[153] Yet standards based on candles were, according to one observer, 'not more scientific, and hardly more accurate, than the barley-corn, of which three went to the inch, as a standard of length'.[154]

The prevailing wax candle standards were widely recognised to be imperfect. The material burnt was of indefinite composition, prompting some writers to claim that the spermaceti available had changed from that in the originally defined candles. By the end of the century wax candles had been extensively investigated and universally condemned. The subject of intensity standards had become of pressing concern to a range of parties.[155] Electric lighting, increasingly promoted from the late 1870s, was a primary motivation. Intense competition between the gas industry and the nascent electric lighting companies was a consequence of the new lighting technology. Within months of the commercial availability of electric lighting systems, the streets and squares of some towns were converted. Among the important technical factors in the competition were the relative cost and quality of gas and electric illumination. For meaningful comparison of the technologies, accurate intensity standards were needed.

Having an immediate financial incentive, photometric investigations proliferated. In 1883, a committee on the Standard of Light for the British Gas Institute investigated the precision of intensity standards, and found variations of between 1% and 16% in the standard candle. A committee for the British Board of Trade found similar variations, and the American Institute of Electrical Engineers set

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[153]*Gas Works Clauses Amendments Act, 1871, schedule A, parts I and II.*

[154]A. P. Trotter, quoted in J. A. Fleming, *A Handbook for the Electrical Laboratory and Testing Room*, Vol II (London, 1907), 240.

[155]*Ibid.*, 238-55.

up its own panel. Improved standards were proposed, investigators usually settling on refining the composition of the combustible agent as the best strategy. The German Association of Gas and Water Engineers defined the *Vereinskerze*, or 'Association Candle', in 1868, which it also manufactured and sold. A paraffin candle having 2% stearine added, it was defined by weight, with 10 candles weighing 0.5 kg. They, too, found their wax candle to be unsatisfactory, rejecting it for the 'Hefner' lamp less than two decades later.

The Hefner proved a more long-lived standard. This unit represented the intensity radiated horizontally by a standard light source consisting of an oil lamp burning amyl acetate. Its inventor, Jacob von Hefner Alteneck (1845-1904), a senior engineer at the Berlin electrical firm of Siemens & Halske, chose a simple hydrocarbon of known composition as the fuel to remove one source of variability from the problem of standardisation. Similarly, the British chemist and inventor A. G. Vernon Harcourt (1834-1919) developed, over the last two decades of the century, standard lamps based on pentane. These were adopted by British industry, and eventually by the national laboratory. The purity of pentane was critical, having to be prepared by a procedure specified by the London Gas Referees.[156]

The setters of standards recognised early on that, like other flame-based standards, the Harcourt and Hefner lamp intensities varied with humidity, air pressure and carbon dioxide concentration. This variability was not seen initially as a disadvantage. On the contrary, gas industry representatives argued that, since the

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[156] *London Gas Referee's Notification for 1901:* 'The pentane is to be obtained from Light American petroleum by three distillations, at 55°C, 50°C and 45°C in succession. The distillate at 45°C is to be shaken from time to time, during two periods of not less than three hours each, with one-tenth its bulk of (1) strong sulphuric acid, (2) solution of caustic soda. After this treatment it is to be again distilled, and that portion is to be collected for use which comes over between the temperatures of 25°C and 40°C. It will consist of pentane, together with small quantities of lower and higher homologues, whose presence does not affect the light of the lamp.' The notification included mandatory testing of the product which comprised evaluation of density in both the liquid and gaseous state, and colour. In practice, pentane to be used in a Harcourt lamp for testing the illuminating power of town gas was prepared in bulk by the gas companies, and then tested by the Referees and supplied in sealed cans to the gas-testing stations, which were under the control of the chemical adviser of the London County Council. See Fleming, *loc. cit.* [56].

flame standards were to be used to evaluate the quality of illuminating gas, both would be similarly affected by atmospheric conditions, and so less variable measurements would be obtained. For those interested in the comparison of electric lamps and the more difficult inter-comparison of gas and electric sources, however, this argument seemed specious; in their view, a photometric standard had to be stable and represent a known value of illuminating power. The judgement of the appropriateness of a standard was consequently far from objective; flavoured by industrial allegiances, it favoured the then-dominant illuminant, gas.

Other practical difficulties with flame standards included controlling the size of the flame, and (in the case of the Hefner lamp) its yellow-orange caste. ‘Our German friends may bask in the ruddy rays of their 0.9 candle Hefner lamp, or our French neighbours enjoy their 10-candle Carcel’, wrote the first president of the Illuminating Engineering Society of London, extolling the virtues of inter-comparable, if nationally distinct, intensity standards.[157] The perturbing factors were carefully detailed in texts on illuminating engineering by the turn of the century. An indication of the difficulty of using flame standards is given by the Assistant in the Photometry Section of the National Physical Laboratory.[158] To make a photometric comparison of the Harcourt pentane lamp with an incandescent lamp, the experimenter first lit the pentane lamp, carefully adjusted the flame height, then ‘threw open the doors and windows of the room’ to allow the flame to stabilise for a half hour. He then gradually increased the voltage of the incandescent lamp to avoid thermal shock to its filament. Once the lamps were ready, the doors and windows were closed, whereupon the visual photometric comparisons could be carried out for ten or fifteen minutes. During the photometric measurements, hygrometer and temperature readings were taken by other observers at several points around the Harcourt lamp. These were later averaged and used to compensate for the known

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[157] S. P. Thompson, *Illum. Eng.* 2 (1909), 813.

[158] C. C. Paterson, ‘Investigations of light standards and the present condition of the high voltage glow lamp’, *J. IEE* 38 (1907), 271-7. Paterson’s career is outlined in Chapter 5.

humidity and temperature dependence of the flame.[159] When the pentane lamp began to diminish in intensity, the experimenter had to repeat the ventilating process.

Partly owing to difficulties such as these when maintaining flame standards, the working standards in use in Britain, America and France were based on incandescent lamps, and rationalised into an international photometric unit in 1909.[160] The German-speaking countries retained the Hefner lamp, which was, however, calibrated with respect to the international standard.[161] Here again, different communities disputed the qualities that were essential to an intensity standard. Supporters of electric lamp standards contended that the Hefner demanded critical measurement of, and correction for, humidity and temperature, rendering the measurement both time-consuming and unreliable. By contrast, supporters of the Hefner argued that its environmental influences were well characterised, and that the lamp itself was straightforward to fabricate by any laboratory. On the other hand, they pointed out, the characteristics of incandescent lamps depended greatly on the materials employed and the method of manufacture, and could not be standardised. Any particular lamp would have to be individually calibrated with respect to a known primary standard. More seriously still, the illuminating power of an incandescent lamp changed unpredictably with age, and was dramatically influenced by its power supply. The only means of minimising this problem were to operate the lamp at reduced power, to limit the time it was on, and to compare it periodically with another type of standard.

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[159]Humidity changes could be a serious problem. One annual report stated that ‘a further mild winter has made it impossible to secure very low values of atmospheric humidity in connection with the realisation of the pentane unit in terms of the values of electric sub-standard lamps. . . the second successive winter this has been impossible [NPL *Report* (Teddington, 1913-14), 50].

[160]P. Fleury, *Étalons Photométriques* (Paris, 1932).

[161]Such national diversity in standards was the norm rather than the exception. The case of the resistance standard has been treated, for example, in K. M. Olesko, ‘Precision and practice in German resistance measures: some comparative considerations’, paper presented at workshop at Dibner Institute, MIT, 16-18 Apr. 1993.

Thus intensity standards, whether based on candles, oil lamps or electric filament bulbs, were disturbingly precarious and contentious. Their combination of physical and social instability rendered them ineffectual; the lack of consensus in these standards, as in other aspects of light measurement, restricted the development of photometry during the following decades. The discord existed at all levels, extending down to groups of investigators in different industries, towns or laboratories.

Despite this lack of consensus, engineers at the local scale employed photometry unproblematically to provide routine information for specific tasks.[162] The Edison company, for example, used a permanent photometric installation as part of the control system for electrical power in one of its generating stations. The photometer, mounted on a graduated iron bar, verified the luminous intensity of the lamps, and a galvanometer monitored the strength of the supply current. The reference source was a ‘standard gas mantle, perfectly adjusted to normal luminous intensity’.[163] The town’s electricity supply was thus in the incongruous position of being regulated in terms of the locally available illuminating gas. Again, the dominant commercial light source was shaping the practice of photometry.

An indication of the predominance of gas photometry as the principal usage of light measurement is shown by an 1870 book, in which W. M. Williams proposed an explanation for the continued prodigious heat and light emission from the sun.[164] His explanation relied upon the assumption that light would pass unattenuated through successive layers of flame, and thus could build up to the level of brightness observed from the solar surface, even if the temperature of the flame was modest. Seeking measurements of flame intensity and transparency to confirm his theory, the author consulted not the optical scientists of the day, but the local gas examiner in Sheffield.[165] This official employed his ‘photometer of the best construction’ in a

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[162]For a particularly standardised measurement protocol, see Abady, *op. cit.*

[163]Alglave, *op. cit.*, 301-4; quotation p. 303 (my translation).

[164]W. Mattieu Williams, *The Fuel of the Sun* (London, 1870), Chap. 7.

[165]By seeking to verify the ‘countability’ of intensity, the author was attempting to verify what Norman Campbell referred to as the third or most quantitative form

series of practical experiments. In a period when the majority of the adepts were to be found in the gas industry, most photometric measurements had this pragmatic and utilitarian flavour.

The dominance of gas photometry began to falter as electric incandescent lamps increasingly were seen to be feasible. By the 1880s, the emphasis in industrial photometry was rapidly shifting away from gas testing to the evaluation of electric lamps.[166] The commercial availability of filament lamps dates from 1879 in America, and a few months later in England and other European countries.[167] An indication of the rapid trend towards 'electrotechnical photometry' is given by the laboratories set up for the judging by Committee of Experiments successive Electrical Exhibitions. In the 1882 exhibition at Munich, the photometric laboratory used numerous intermediate gas-burner standards. The following year, the Exhibition at Vienna did away with these in favour of electric lamps. The organisers justified the change in terms of the ease of use and stability, at least over short terms, of the latter.[168] In common with the previous examples, the choice of intensity standard in this case had other than a purely technical motive – but now the electric lamp, not gas, was in control.

The nineteenth-century photometer

The increasing employment of photometry was accompanied by a stabilisation of its technology. Photometers came to exemplify the goals of precision and

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of measurement. Lighting was generally accepted to be of the 'rankable, but not necessarily combinable' form (Campbell's class 2) at this time.

[166]The decline of routine photometric testing of gas supplies was accelerated by a trend towards the simpler technique of calorific testing, which 'quite a number of the leading companies' adopted by 1910 [L. Gaster and J. S. Dow, *Modern Illuminants and Illuminating Engineering* (London, 1920), 72-3].

[167]For general histories of the evolution of electric lighting, see, for example, J. A. Cox, *A Century of Light* (N. Y., 1980) and W. Schivelbusch, *op. cit.*

[168]A. Palaz, *op. cit.*, 181. The widespread contemporary application of public electric lighting is illustrated by E. Alglave and J. Boulard, *op. cit.*; the Paris Expositions of 1878 and 1881 were important showplaces for the new technology.

reliability increasingly sought of their users, but paradoxically revealed the weakness of human observers in the process.

All standards work, and the majority of scientific applications, employed visual photometers. Devices for light measurement had been designed sporadically through the century for specific researches. By the end of the century, these had evolved into impressively refined products which nevertheless employed the observational principles established by previous generations. Typical instruments often included prisms, polarisers, viewing telescope, translucent or reflective screens (prepared with great care to yield particular viewing characteristics), graduated goniometers or scales. Of the dozens of elaborated versions, serious practitioners used only a few in their work.[169] The principal technical innovation was improvement in the 'photometric heads' used to combine and observe the illumination produced by two light sources. Visual photometry relied upon comparing two sources of light, one the sample and the other a known reference. Comparison proved more accurate when the two intensities were in proximity.

The most enduring photometer design was Bunsen's 'grease-spot' photometer, invented in 1843 for an investigation of the chemical action of light.[170] It relied on the fact that a spot of grease or wax on paper appears bright when illuminated from behind, and dark when lighted from the front. By placing the two lamps to be compared on either side of such a screen, the intensities could be adjusted to equality by noting when the grease spot disappeared.[171] The design, employing readily available materials, embodied the majority view that light measurement could be made an everyday task. Experimenters nevertheless invented numerous variants of Bunsen's apparatus. Mirrors were added to allow both sides of the screen to be viewed simultaneously, or to alternate the side of the screen illuminated; the simple greased paper was replaced by materials having more optimal transmission and

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[169] Palaz, *ibid.*, Chap. 2, describes over two dozen variants in considerable detail.

[170] R. Bunsen and E. H. Roscoe, *Phil. Trans.* 149 (1859), 891.

[171] In practice, this condition occurs only if the reflectance of the paper equals the transmittance of the grease spot. Practitioners overcame this difficulty by either equating the *contrast* of the spot on either side of the screen, or by causing it to disappear on each side and then averaging the resulting measurements.

reflection characteristics, or more stable properties. By the end of the century, practitioners of photometry had evaluated the ease of use and repeatability of many types of visual instrument and generally favoured the new head invented by Otto Lummer and Eugen Brodhun in Germany in 1889. This scheme, designed to counteract the perturbing factors by then identified, provided a 'visual

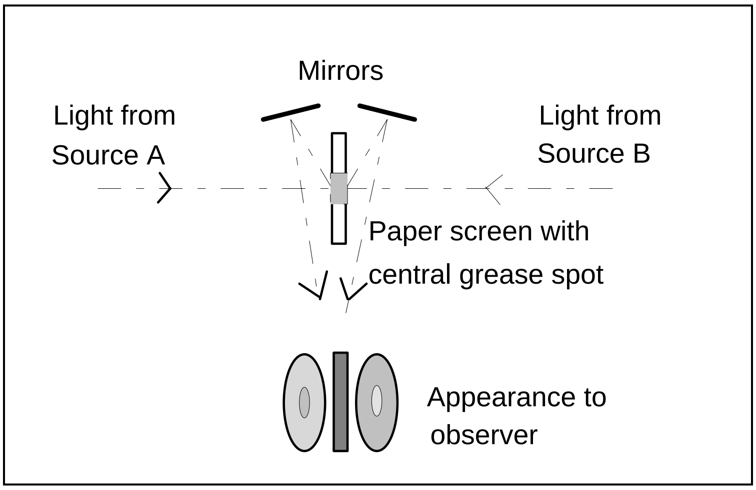

Fig. 5 Bunsen grease-spot photometer head

field' consisting of two or more immediately adjacent regions from the two light sources. The screen, instead of being a combination of reflecting and translucent areas, was simply a diffuse reflector and thus easier to fabricate. The precision-manufactured prisms caused the images of the two sides of the screen to be combined when viewed through an eyepiece, yielding a central spot for one side and an outer ring for the image from the opposite side of the screen. As in the grease-spot head, the balance of the two sources was indicated when the division disappeared or had minimum contrast. Its inventors claimed their photometer to be some eight times more precise than the grease-spot photometer. The Lummer-Brodhun version became the standard for the German gas and electric lighting industries following its commercial manufacture beginning in 1893. This photometer head and its variants, incorporating the values of 'precision' and 'reliability', served routinely in photometric laboratories for the following forty years. There were, nevertheless, detractors. A dissatisfied British user, for example, complained that 'the telescope or microscope is considered to be an indispensable adjunct to any instrument in

Germany', and that as a consequence the one-eyed observation was fatiguing, and the photometric measurement depended on the quality of focus.[172]

While it comprised the instrumental heart, the photometric head was not the entire photometer. To match the sample intensity to that of the reference light source, the reference intensity had to be adjusted by some convenient means, the most important of which are shown schematically in Fig. 7.

Most of the preferred methods related the adjustment of intensity to a simple mathematical relationship. A laboratory-based photometer had few constraints on physical space or on the duration of a measurement, unlike an instrument designed for astronomical use, and so the adjustment of the reference intensity used in the photometric comparison usually relied on moving the lamp away from the screen so

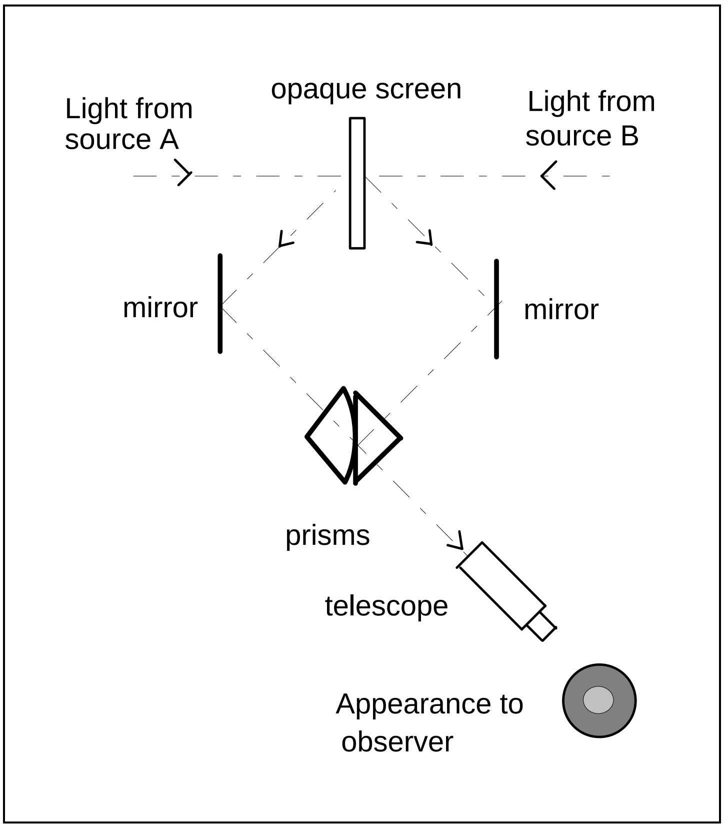

Fig. 6 Lummer-Brodhun photometer head

[172]A. Trotter, *Illumination: Its Distribution and Measurement* (London, 1911), 105.

that the brightness decreased according to the inverse-square law (see Fig. 7a). The photometer 'bench' contained one or more 'carriages' to move either the photometer head or one of the light sources. To measure light sources of very different intensity, long photometer benches were necessary. One constructed at the National Physical Laboratory in 1905 was 90 feet long, running the length of a specially constructed building.[173] With such apparatus, rapid adjustment of the reference intensity proved cumbersome. Operators increasingly became aware that practical factors such as speed, ease of adjustment and comfort were critical to the measurement accuracy obtained. One practitioner described his technique for equating two lights:

> The secret is this. First you oscillate the photometer until you get the best balance you can, then you oscillate one of the standards, one person oscillating it while the second person is getting a final adjustment of the photometer.[174]

Application of the inverse-square law was ill-suited to astronomical usage, however, where apparatus was necessarily mounted on the telescope. In the rotating sector method devised by Talbot, the experimenter exposed the reference screen to light from an opaque disk having a cut-out sector (see Fig. 7b). In later versions devised by William Abney, the sector angle could be adjusted as the disk rotated, allowing continual and rapid matching of its intensity to that of the unknown. For laboratories having less space or fewer assistants, other methods of intensity adjustment found application. The second most popular adjustment method was based on Malus' law of polarisation (see Fig. 7c). The rotation of one polariser by up to 90° relative to another provided a precise method of varying intensity by 100%. Other, less reliable, methods relied on tilting a reference surface (which provided an analytically known variation in reflectance only for 'ideal' materials) or on estimates of visual acuity that were based on viewing text. These latter were employed mainly by enthusiasts or inventors unfamiliar with the practicalities, and were avoided by serious practitioners.

Optical density wedges found frequent application in astronomy and photography (see Fig. 7d). They were, however, less fundamental than the preceding

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[173]*NPL Report* (Teddington, 1905).

[174]M. Ayrton, *J. IEE* 32, 206.

methods. A wedge was usually formed by a thin prism of grey or ‘neutral’ glass. Other alternatives included wedges of gelatine and fine lampblack, or coloured liquids.[175] If the glass was homogeneous, the logarithm of its transparency was proportional to its thickness. In practice, no such mathematical relationship was used; instead of relying on the theoretical relationship, the experimenter measured the

[175]J. Walsh, *Photometry* (London, 1926), 179.

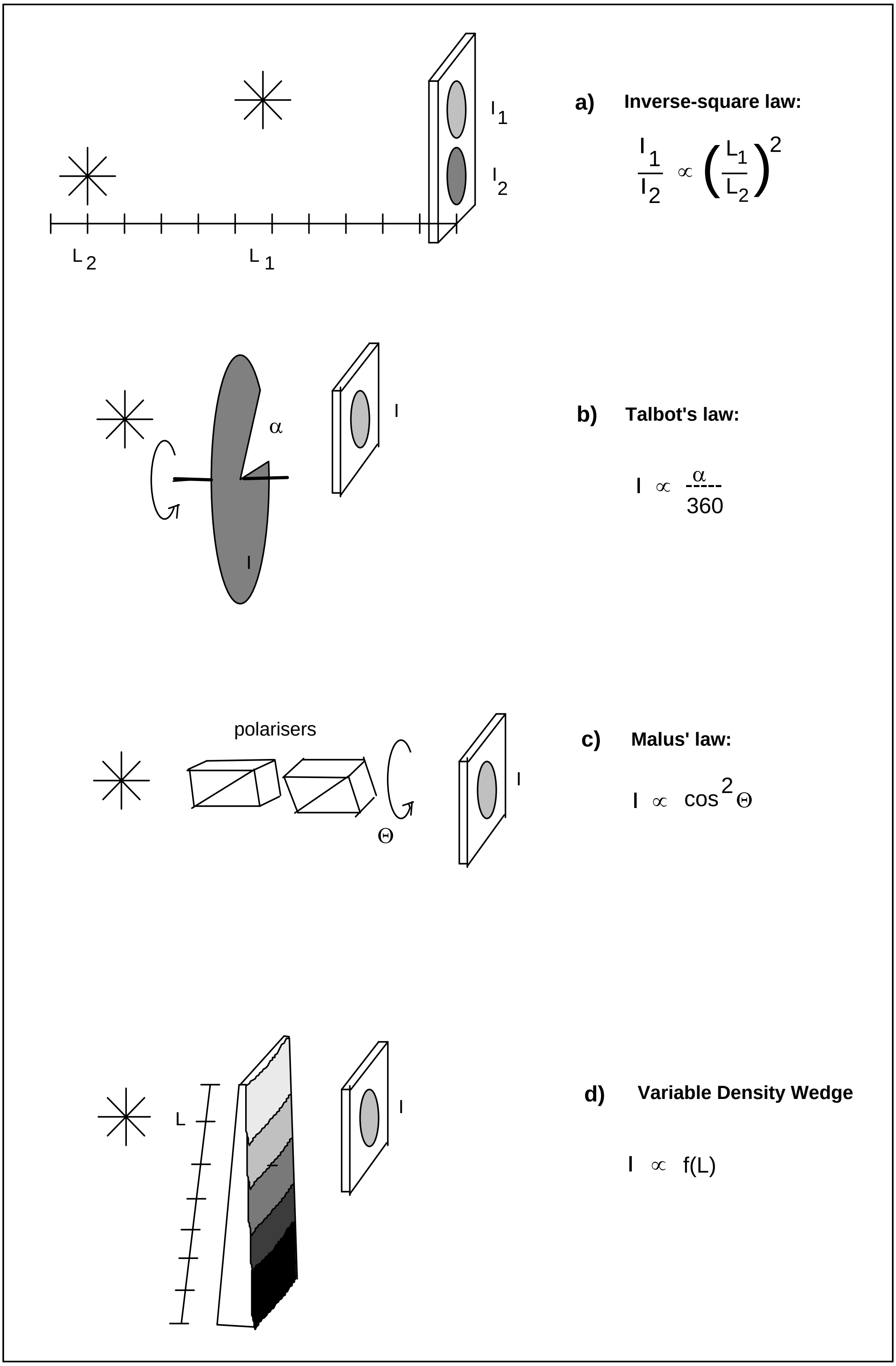

Fig. 7 Some methods used to adjust the reference intensity in visual photometry.

transparency of the wedge at known positions along its length using one of the above techniques.

But, besides the increasingly sophisticated equipment, there was the central importance of the observer himself to the measurement.[176] The physicist René Blondlot was typical in stressing the difficulty of visual observations when he cautioned that 'the observer must play an absolutely passive part, under penalty of seeing nothing'.[177] Each careful photometric observer developed his own method for avoiding errors. William Abney wrote in 1891:

> This operation of equalising luminosities must be carried out quickly and without concentrated thought, for if an observer stops to *think*, a fancied equality of brightness may exist, which other properly carried out *observations* show to be inexact.[178]

Abney's method of differentiating between 'fancied equality' and 'properly carried out observations' was thus simply to dissociate the mind from the eye. Far from being deemed intrinsically problematic, the reliance upon a mental technique was interpreted by practitioners as a mark of expertise. By the following decade, such unproblematic separation of psychological and physical effects no longer seemed practicable to most scientists.

Problems of visual intensity measurement

The difficulties of good photometric practice cannot be overstated. Itemising the precautions he took to ensure good visual comparisons in stellar photometry, John Parkhurst wrote in 1906:

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[176] *Himself*, because I have found no record of female photometric observers before ~1905, when routine electric lamp measurements began to call for patient, careful and low-paid employees. The requirements were similar to those at Airy's Greenwich Observatory, which had demanded 'indefatigable, hard-working, and, above all, obedient drudges' [S. Schaffer, 'Astronomers mark time', *Sci. Context* 2 (1988), 120].

[177] R. Blondlot, *"N" Rays*, transl. by J. Garcin (London, 1905), 82.

[178] W. de W. Abney, *Colour Measurement and Mixture* (London, 1891), 79; author's italics.

(1) The two stars to be compared were made parallel to the line of the eyes. To the writer this precaution was of the utmost importance, for if two equal stars were placed in a vertical line the lower would appear more than half a magnitude the brighter.
(2) Two or three comparison stars were used at each observation if they could be found in proper distances and magnitudes, though this rule often conflicted with the two following.
(3) The stars to be compared should be in the same field, and
(4) The interval in brightness should be less than half a magnitude. If this limit was exceeded the comparisons were weighted in the reductions, inversely as the interval.
(5) Prejudice which would arise from anticipating the star's expected changes, was avoided by postponing the reduction till the maximum or minimum was completed. The observing list was long enough so that the previous observations were usually forgotten at the time of a comparison.
(6) The comparison of too bright stars was avoided by reducing the aperture when necessary.
(7) Light in the eyes was avoided by using for recording a one-candlepower incandescent lamp, so shielded as to illuminate faintly a circle one or two inches in diameter on the record book.[179]

Parkhurst's item (5) stresses the measures necessary to avoid involuntary bias by the observer, and echoes the words of Benjamin Thompson a century earlier. Parkhurst's other precautions indicate the physiological limitations of visual observation. His list emphasises the sheer difficulty of obtaining meaningful results. For Parkhurst, the measurement of intensity was highly problematic.

The photographic photometry of small light sources such as stars entrained its own unique problems, the most serious of which was that it did not agree with visual determinations. Instead of Pogson's ratio of about 2.5 for the difference between magnitudes, a value closer to 3 was usually found, depending on the particular type of star in question and the type of photographic plate used. The problem, astronomers concluded, was due to the different colour sensitivities of the eye and photographic materials. To settle the issue, the Permanent Committee of the Astrographic Congress meeting in Paris in 1909 resolved to equate photographic and visual magnitudes for white type Ao stars.[180] As the visual photometric scale had been defined previously by Pickering and was more firmly established due to the publication of extensive catalogues, this required an adjustment of the photographic photometric scale, also set

[179]Parkhurst, *op. cit.* 2-3.

[180]Stellar classifications had been increasingly refined over the previous decade by the examination of stellar spectra.

by Pickering.[181] This *ad hoc* decision thus linked two techniques of light measurement according to a rather arbitrary criterion, namely the particular emission spectrum (and apparent colour) of a common type of star. Quantification in terms of visual and photographic magnitudes already relied on the arbitrary definition of magnitude. That astronomers accepted such a chain of definitions indicates their beliefs concerning the overriding utility of *some* numerical measure for relating and recording stellar intensities.

The increasing usages of photometry by the turn of the century were accompanied by criticism from their users and cautions from experts. Hermann von Helmholtz had written of intensity measurement that

> the whole region is closely entangled with physiological problems of the utmost difficulty, and moreover the investigators who can make advances are necessarily limited, because they must have long practice in the observation of subjective phenomena before they are qualified to do more than see what others have seen before them.[182]

Even careful attention to technique by meticulous observers resulted in measurements that were of doubtful accuracy. Measurements were affected by several subtle considerations that could be easily missed by a novice investigator. ‘Photometry is not a simple and well-defined subject’, wrote the author of another book,

> Bare directions will not suffice, but the practitioner must bring to the task a judgement trained for instrumental manipulation and an appreciation for the many modifying influences that the measurements which he obtains may possess in value.[183]

Indeed, the *modifying influences* could seriously affect the accuracy of the measurement. Until these influences could be identified and themselves quantified, implied the author, photometry would yield imprecise and unreliable results.

Foremost among the modifying influences was the basic problem of estimating the brightness of light by eye. As early as 1729, Bouguer, criticising his

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[181]Pickering’s *North Polar Sequence*, consisting initially of the photographic magnitudes of 47 stars, was used. The Sequence included 96 stars by 1912.

[182]H. von Helmholtz, *Physiological Optics* - *Vol I*, transl. by J. P. C. Southall (N.Y., 1924), viii.

[183]P. Stiles, *Photometrical Measurements*, quoted in J. W. T. Walsh, *Photometry* (London, 1929), vii.

contemporaries' ideas of light intensity, had objected that the sensitivity of the human eye varied from time to time, and that too much variation would be found among different observers to allow precise and consistent results.[184] Bouguer's nineteenth century successors, usually seeing photometry as a 'simple and well-defined subject', frequently started afresh only to rediscover the problems.

Another physiological factor frequently overlooked was the limited range of brightness over which the eye could precisely match two lights. One practitioner, studying photometry for various colours of light, noted:

> If the intensity is too strong, the tired eye partially loses its ability to recognise small differences of intensity; if the light is too weak, on the contrary, the eye no longer easily grasps the difference of intensity. . . and the measurements are similarly less precise.[185]

As noted above, too little or too much mental concentration also was undesirable. Similarly, the observing time and state of health of the observer were relevant to the results obtained. Writing 36 years later, another commentator wrote:

> Looking at the photometer screen for too short a time reduces the precision, but this happens also if the period is made too long. . . the accuracy, or rather the precision, obtainable in photometric work depends largely on the individual. . . As in everything, experience tells also in this class of work. Even the condition of the observer is of importance, and it will be quite obvious that a person out of health will be less reliable – under otherwise equal conditions – than a healthy individual.[186]

For accurate work, no more than a dozen measurements could be taken before resting the eyes.

An ill-defined range of acceptability seemed to pertain for each of these variables. Even the mental state and expectations of the observer were an important factor. 'The unconscious mental bias' that could result if an observer became aware of any progressive tendency in his readings was avoided in some laboratories by arranging that 'the observers shall work in pairs, each one noting down the readings

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[184]See Chapter 2, ref [8].

[185]H. Trannin, 'Mesures photométriques dans les differentes régions du spectre', *J. Phys.* 5 (1876), 297-304; quotation p. 304 (my translation).

[186]H. Bohle, *Electrical Photometry and Illumination* (London: 1912), 82.

obtained by the other'.[187] Taking into account these various factors, an unfatigued observer, using convenient apparatus and matching light sources that were neither too bright nor too dim, could obtain accuracies better than 1%; in poor conditions, accuracy might be an order of magnitude worse.

Ominously for the subject, a fundamental relationship between the observations of the human eye and any physical measurement was difficult for many to countenance:

> Photometry is not the measurement of an external or objective dimension or force, but of a sensation. It is difficult to make a quantitative measurement of our sensations. Two pigs under a gate make more noise than one pig, and while it is possible to measure the amplitude of the vibrations of air which produce sounds, and to estimate those which correspond to the faintest audible sound and those which cause the roar of a large organ, we know little of the quantitative measurement of sound. The attempt to apply measurement to sensations of smell has not met with success, and in spite of the delicacy with which different sensations of taste may be discriminated, it not only seems impossible to measure taste, but there appear to be physiological reasons for a rapid approach to a saturated condition of the sensation. A similar difficulty arises in the action of light on the eye.[188]

For this author, photometry was synonymous with visual observation, being not *a measurement of an external dimension* but rather *a sensation*. He saw no natural connection between light intensity and a physical quantity such as energy. Such a view precluded replacing the eye by a physical detector, because such a replacement would somehow have to mimic the response of the eye, faults and all. At the turn of the century, in any case, practitioners saw few serious alternatives to human observation in the measurement of light. For engineers, there was no physical detector of light available that had the necessary attributes, namely ease of use, reliable properties and a spectral response similar to that of the eye.

By the end of the century, investigators were usually aware of physiological factors, and employed photometers that allowed the eye to make immediate, side-by-side comparative measurements as described above. Measurement again became problematic, though, when the light sources being compared were of different colours. If the flame (or star, or light transmitted through a coloured medium) differed in

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[187] J. W. T. Walsh, *Photometry* (London, 1926), 316.

[188] Trotter, *op. cit.*, 67.

colour from the standard used for comparison, the observer frequently found it difficult to determine a unique relationship between them. The subject could be matched by various combinations of coloured lights, and the match would differ for observers having different colour vision. As different light sources were composed of different distributions of colour, this situation posed severe problems: not only did the result depend on the observer, but on the type of light as well. Colour equality was a subjective attribute that could not be reified. Only when light sources could be compared colour-by-colour could an ‘additive’, unique mathematical relationship (Campbell’s ‘class 3 measurement’) linking them be found. This pessimistic conclusion was pointed out by various writers on the subject, but was by no means universally accepted. William Abney, for example, reported an extensive body of work on colour photometry, claiming to have no difficulty in matching different coloured lights precisely.[189]

Beyond the measuring technique itself, the units used in the measurement and description of light could cause considerable confusion, even among engineers. What, exactly, was being measured? One authority related his experience with an American associate:

> An expert, called in to interpret a clause in an electric-lighting contract between a town near New York and the local electrical company, with regard to some 2000 nominal candle-power arcs, expressed his opinion as follows: ‘The arc lamps are suspended at the cross roads, and each one, therefore, sends its light in four directions; one cannot, therefore, expect to get 2000 candles in each direction. The 2000-candle arc arranged for in the agreement was one sending 500 candles down each road’. We do not wish to make fun of this expert, for in truth he is a very sensible man.[190]

The arc lamps, explained this authority, produced the equivalent of the light of 2000 candles in every direction. The quoted expert had confused a unit of intensity (candle-power) with a unit of total quantity. With practitioners self-trained and originating from a variety of technical backgrounds, photometry had little prospect of advancement. As late as 1914 photometric concepts and the practice of photometry

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[189]Abney’s researches, widely cited, included: ‘Colour photometry’ (Bakerian Lecture, with E. R. Festing) *Proc. Roy. Soc.* 40, 238; *Colour Vision* (London, 1895); *Colour Measurement and Mixture* (London, 1891); and, *Researches in Colour Vision and the Trichromatic Theory* (N.Y., 1913).

[190]P. Blondel, *Electrician* 33 (1894), 633.

were perceived as difficult, non-intuitive, and a serious hindrance to progress. In a preface to a book on illuminating engineering, Arthur Blok wrote:

> Prominence is given to the 'flux of light' conception, as this seems in great measure to remove a sense of intangibility which the problems of illumination so often present to those who approach them for the first time.[191]

Even the inverse-square law, accepted since the time of Bouguer, was disputed by some engineers:

> as far as the evidence goes. . . photometry is on a fundamentally wrong basis, and. . . it is absolutely impossible to compare and to express as the function of one and the same unit, the luminous intensity of a *source* of light reduced theoretically to a mathematical point, and that of a luminous beam of which the rays are parallel or sensibly so.[192]

The author was complaining about the theory of lighthouses.[193] British lighthouse lantern sizes had long been designated as 'first order', 'second order', etc. It was now (1893) proposed to replace these by candlepower ratings. The author concluded that 'the values of the luminous intensities attributed to lighthouses and to projectors have not any physical meaning'. In his mind, the quantitative measurement of light was simply not feasible. Many others agreed that the concepts of intensity were flawed. Hospitalier proposed relating light *intensity* to a magnetic field, and *candle power* to a magnetic pole, as analogies. The appropriate physical analogy to apply to light was far from obvious. By the end of the century, however, most engineers favoured the system of photometric units introduced in 1894 by André Eugène Blondel (1863-

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[191]A. Blok, *The Elementary Principles of Illumination and Artificial Lighting* (London: 1914), v.

[192]M. Hospitalier, 'Photometric Fantasies', *L'Industrie Électrique*, reprinted in *Electrician* <u>32</u> (1893), 59-60.

[193]The design of lighthouses had occupied such scientists as Michael Faraday and Augustin Fresnel earlier in the century. Fresnel (1788-1827) spent the last few years of his life devoted to work for the French lighthouse commission, which included designing stepped lenses to improve collimation and beam intensity. Some 65 years later, André Blondel followed him by being employed by the École des Ponts et Chaussées and the Service Central des Phares et Balises. Blondel used his experiences with lighthouse design and electrotechnics to devise the system of photometric units later adopted by International conferences. Because of the previous existence of national committees and an international association of lighthouse authorities, the otherwise influential Commission Internationale de l'Éclairage (discussed in Chap. 7) steered away from this subject in light measurement and standardisation.

1938) based on the concept of ‘luminous flux’, and which defined illumination according to the flux received by a unit surface. His system was adopted in 1896 by the International Electrical Congress at Geneva, and subsequently by the International Illumination Commission and the International Conference on Weights and Measures in following decades. While still unintuitive, Blondel’s system was self-consistent and presented a close similitude to other physical units.

Perhaps even worse than being contentious, the practice of photometry was more often ignored. Allied closely, as they were, to standards in the gas industry, developments in photometer design caused little notice among scientists. In accepting an award for his design at the 1893 Chicago Exposition, Lummer chided his academic colleagues for having treated photometry ‘rather slightingly’. He claimed that they had neglected the subject until the needs of the illumination industry and the public had shown them its importance.[194]

Quantifying light: *n*-rays vs blackbody radiation

The scientific and engineering communities that were beginning to crystallise around the subject at the end of the nineteenth century followed essentially parallel but independent courses in light measurement. In the scientific community there was an interest in the use of quantitative light measurement, with a growing tendency towards physical methods of detection. The twentieth century opened with some notable scientific applications of intensity measurement. A transition was occurring, among physicists at least, from acceptance of visual methods of observation to a preference for physical methods. Two contrasting and important cases illustrate this trend: *n*-rays and blackbody radiation.

The case of *n*-rays has popularly been cited as an example of ‘unscientific’ methods and ‘anomalous physics’.[195] In the context of photometry, however, and perhaps less Whiggishly, it illustrates the profound difficulties of visual observation

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[194]Quoted in D. Cahan, *An Institute for an Empire: The Physikalisch-Technische Reichsanstalt 1871-1918* (Cambridge, 1989), 106-7.

[195]See, for example, I. Langmuir and R. N. Hall, ‘Pathological science’, *Phys. Today* 42 (1989), 36-48, an edited transcript of a talk given by Langmuir in 1953.

when applied to subtle intensity differences. For scientists of the day, the *n*-ray case came to illustrate the dangers and undesirability of attempting to *measure* using the human senses. On 23 March 1903, in the heady decade following the discovery of *x*-rays, α-rays and β-rays, the French scientist René-Prosper Blondlot (1849-1930) announced his discovery of what he termed '*n*-rays'.[196] He reported that these rays were first produced from a heated filament in an iron tube, and emitted through a thick aluminium window. The primary demonstration of the rays was to increase apparent brightness.[197] Blondlot found that if a white card was illuminated with extremely dim light – just above the threshold of visibility – his *n*-ray source would make the card much easier to see. The same effect was produced on other objects illuminated by weak light sources such as fluorescent screens or electric sparks. He and several other investigators used this intensity variation to study the properties of *n*-rays. Blondlot himself published 10 papers on the phenomenon in 1903, and a dozen in 1904 in the *Comptes Rendus* alone. Over a 16 month period, British, German and American researchers tried with little success to replicate Blondlot's results. But at least 14 French scientists, most of them initiated by Blondlot himself, seemed to have the knack.[198] The observations required not only dark adaptation but also a progressive sensitisation to extremely feeble light sources, a process that could demand weeks of training: 'to observe *n*-rays or similar agents, a special exercise of the vision is necessary. . . we must adapt our organs to a function completely different from that which we normally demand of them'.[199] While such visual training had

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[196]R. Blondlot, 'Sur une nouvelle espèce de lumière', *Comptes Rendus* 137 (1903), 735-8. Blondlot was professor of physics at the Université de Nancy (hence the appellation 'n' rays), and a corresponding member of the Académie des Sciences. He was known for his previous investigations of *x*-rays.

[197]There were recent antecedents for such observations; indeed, Blondlot's method was current in electromagnetic research from the early 1880s, when Heinrich Hertz explored the characteristics of radio waves by noting the effect of ultraviolet light on the intensity of electric sparks, to the early 1900s, when Lee de Forest observed that a gas flame brightened when a spark gap was operating nearby, inspiring his invention of the triode valve.

[198]M. J. Nye, 'N-rays: an episode in the history and psychology of science', *Hist. Stud. Phys. Sci.* 11, (1980) 125-56.

[199]R. Blondlot, 'Sur une méthode nouvelle pour observer les rayons N et les agents analogue', *Comptes Rendus* 139 (1904) 114-5 (my translation).

been preached as standard practice in photometry, through 1904 several physicists raised objections about Blondlot's methods. Typical among them was a review of Blondlot's book, *"N" Rays*. Echoing the words in Helmholtz's *Physiological Optics*, the reviewer's central criticism dealt with the *subjectivity* of visual observations:

> the so-called proof of their existence depends, not on objective phenomena that can be critically examined, but on a subjective impression on the mind of the experimenter, who sees, or imagines he sees, or imagines he does not see, a slight change in the degree of luminosity of a phosphorescing screen.

And, in closing:

> these observers have been the subjects either of an illusion of the senses or a delusion of the mind.[200]

In response to his critics, Blondlot supplemented his visual detection method by a seemingly conclusive *physical* method of determining brightness: he exposed half a photographic plate to the light from a spark illuminated by *n*-rays, and the other half while the spark was shielded from the rays. For each exposure, Blondlot moved the plate manually back and forth a number of times between these conditions to minimise the effect of any external perturbations such as a gradual change in the intensity of the source. The photographic results, like his previous visual observations, showed remarkable statistics. Of forty such experiments, just 'one was unsuccessful' in showing a 'notably more intense' impression under *n*-ray illumination. He concluded that the 'constancy of the results is an absolute guarantee of their worth', and that he had 'succeeded in recording their action on the spark by an objective method'.[201]

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[200] J. G. McKendrick, 'The "N" Rays', *Nature* 72 (1905), 195.

[201] R. Blondlot, *"N" Rays*, transl. by J. Garcin (London, 1905), 61-8.

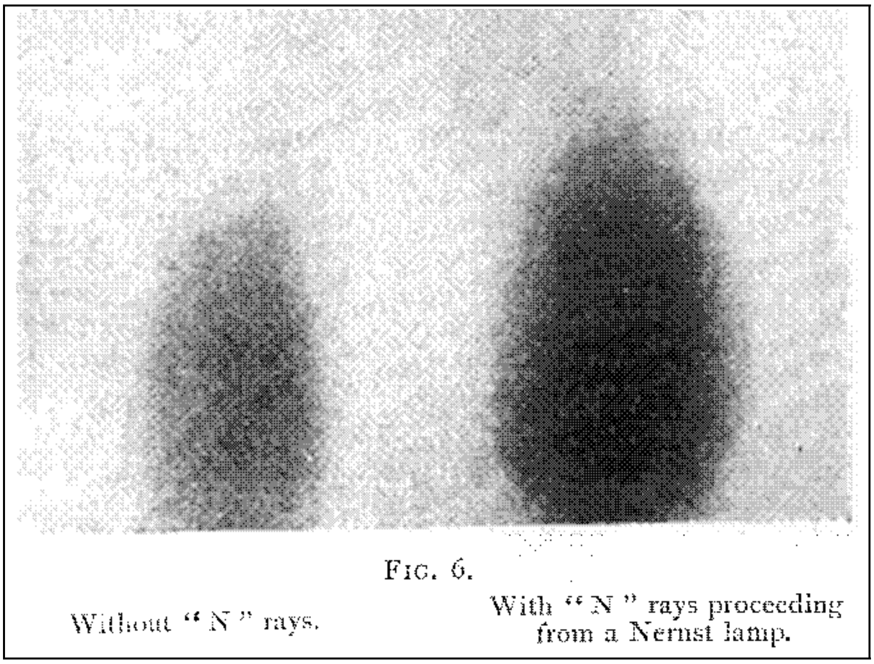

Fig. 8 Physical proof of *n*-rays, from R. Blondlot, *"N" Rays* (London, 1905), facing p.66. The lines in the image are an artefact of the reproduction process.

For Blondlot, this physical technique was a direct analogue of his visual methods, and necessary only for experimenters not having the requisite observational skills. He made no attempt to exploit this physical technique, nor to suggest that others develop it further. It was merely a gambit to convince his vocal critics. His writings suggest that Blondlot's aim was to discover new phenomena, not to restrict himself to the mere establishment of the exact mathematical relationship between intensity and *n*-rays. Quantification had a distinctly secondary role in such an agenda.

The *Revue Scientifique* carried out its own investigation in late 1904, and concluded that Blondlot and his followers were all victims of autosuggestion, that no accentuation of light intensity in fact occurred, and that *n*-rays did not exist. *The Electrician* reported at the end of the year that 'this extraordinary controversy goes merrily on', but Blondlot published no papers in the *Comptes Rendus* after 1904.[202]

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[202]Anon., editorial, *Electrician* 54 (1904), 296.

This new scepticism over visual methods parallels and contrasts nicely another case of the measurement of light from hot bodies. This second case was widely perceived as a notable success for 'physical' measurement by contemporary scientists. Radiometry, the close cousin of physical photometry, was mapping the blackbody spectrum between the 1880s and 1920s. Among the experimentalists were some like Heinrich Rubens (1865-1922) who were to seek Blondlot's *n*-rays without success. Indeed, Blondlot later corresponded with Rubens and publicly allied his own work to Rubens' researches.[203] Rubens refined the measurements of the emission from heated bodies and extended them from the visible to the far infrared spectrum. By the closing decade of the century, the experimental work had been sufficiently refined to permit some important laws to be identified.[204] Between 1887 and 1906, this close interaction between experimental work and theoretical derivations culminated in the work of Max Planck (1858-1947). The results were the first evidence for the quantisation of energy.[205]

What did these radiometric studies have that *n*-ray research lacked? Why was their reliability almost unquestioned, and quickly accepted by theorists? The novelty of *n*-rays cannot be invoked: the period was swamped by novel phenomena that were unanticipated by either theory or prior experiments. Yet in the eyes of contemporary scientists there were some key differences. First, the blackbody results were repeatable: measurements tended to agree between observers. Although Blondlot claimed that he had achieved excellent repeatability, his results could be reproduced only with great difficulty, if at all, by others. This was a disturbing characteristic of what appeared, on the face of it, to be a straightforward experiment. By contrast, the

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[203]Blondlot, *op. cit.*, 13, 17, 30.

[204]Friedrich Paschen (1865-1947) found the wavelength of peak emission to be inversely proportional to temperature. Encouraged by the reliability of the data, theorists such as the Russian W. A. Michelson (1860-1927) and the German H. F. Weber (1843-1912) tried to fit formulas to them.

[205]Histories of blackbody radiation research include H. Kangro, *The Early History of Planck's Radiation Law* (English translation, London, 1976) and T. S. Kuhn, *Blackbody Theory and the Quantum Discontinuity* (Oxford, 1978). A good contemporary survey is W. W. Coblentz, 'The present status of the constants and verification of the laws of thermal radiation of a uniformly heated enclosure', *JOSA* 5 (1921), 131-55.

blackbody measurements, which involved meticulous experimental arrangements using *physical* rather than *physiological* detectors, could be understood by all interested physicists, and verified at least in a qualitative way. In contrast to Blondlot's 'threshold' method of observation, the blackbody measurements were intrinsically numerical; as such they could roughly be approximated by crude observations and then increasingly refined. The statistical calculation of the uncertainty of such measurements instilled more confidence than did the mere detection achieved by Blondlot. The blackbody experimental evidence was not an 'all or nothing' affair. Expressed in another way, the blackbody research was founded on what Campbell was to call 'class 3' measurement, i.e. fully quantitative determinations. The *n*-ray results, in contrast, never sought to go beyond demonstrating the *presence* or *absence* of an intensity change, even when Blondlot claimed to have produced excellent statistics for such detection. They constituted Campbell's crudest 'class 1' observation, in which intensity measurement is limited to a 'greater than' or 'less than' decision. What appears to have disturbed contemporary physicists was that Blondlot restricted his observations to this lowest common denominator and made no serious effort to use available and, in their view, superior techniques. His methods, in short, appeared perversely and persistently old-fashioned.[206]

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[206]These characteristics were subsequently categorised by the American industrial physicist Irving Langmuir as 'pathological science' [Langmuir & Hall, *op. cit.*, 44]. His symptoms of such a science are the following: (1) The maximum effect is produced by a causative agent of barely detectable intensity, and the magnitude of the effect substantially independent of the cause; (2) the effect is of a magnitude that remains close to the limit of detectability, or many measurements are necessary because of the low statistical significance of the results; (3) claims of great accuracy are made; (4) criticisms are met by *ad hoc* excuses; (5) the ratio of supporters rises initially and then falls continuously. Langmuir's points are questionable; symptoms 3 and 4, for example, are not particularly strong factors in the ultimate rejection of observations. The definition of 'great accuracy' and '*ad hoc* excuses' could differ for supporters and opponents of the evidence. Even more tellingly, the number of supporters of a new phenomenon may vary for other reasons than internal scientific consistency or methodological rigour. Such sociological causes are ignored by Langmuir. However, his first and second points highlight the difference between a truly quantitative measurement and threshold detection. This single, crucial difference appears to have been central to the rejection of Blondlot's results and the acceptance of blackbody data. Intriguingly, Langmuir, who had used visual photometry during his incandescent

A second difference between *n*-ray observations and blackbody measurements was that the latter were perceived as being ‘objective’. The observer merely ‘recorded the instrument reading’, and played no part in judging the result.[207] Even with Blondlot’s photographic technique, his critics pointed out, he had to *judge* how long to leave his plate in the exposed and unexposed positions.[208] Even so, such physical evidence could have been much more easily confirmed than the visual threshold technique Blondlot used almost exclusively; the photograph was capable of providing ‘class 3’ information if the grey scale were calibrated. There are few records of other investigators attempting to detect *n*-rays by physical methods, however.[209] This illustrates that scientists were concerned not just by the need to use the eye, but by the sum of Blondlot’s experimental methodology. By the time Blondlot published his photographic evidence it was too late; the scientific community had already dismissed his results.[210]

The putative differences of quality between visual judgements and radiometric measurements do not appear marked in retrospect. Both were vulnerable to numerous sources of systematic error, but, significantly, radiometric methods confined their systematic errors to physically determinable causes. Errors might be caused by stray

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lamp research, cited two cases of visual detection (*n*-rays and scintillation counting) as prime examples of ‘anomalous science’.

[207]The identification of physical photometry with ‘objectivity’ was implicit and persistent from the turn of the century. See, for example, E. Liebenthal, ‘Photometrie, objective’ in *Phys. Handwörterbuch* (Berlin, 1924).

[208]Blondlot claimed to have used a metronome to time the period allotted to exposing the plate in the two positions, but qualified this by noting that the method did not yield good photographs for publication. The reproduced figure did *not* use such timing.

[209]One such case, published weeks after Blondlot’s evidence, was G. Weiss & L. Bull, ‘Sur l’enregistrement des rayons N par la photographie’, *Comptes Rendus* 139 (1904), 1028-9. Repeating his experiment, they were unable to reproduce Blondlot’s results: ‘dans aucun cas nous n’avons pu obtenir de résultat positif’.

[210]Allan Franklin, in *The Neglect of Experiment* (Cambridge, 1986) and *Experiment, Right or Wrong* (Cambridge, 1990), discusses factors determining the acceptance of new experimental data in sub-atomic physics. He argues persuasively that the data and statistical evidence are a small part of the acceptance, and that other less tangible factors such as the reputation of the experimenter and the perceived complexity of the experiment are important factors.

light, drifts of readings caused by air fluctuations of the galvanometer, electrical interference of the detector caused by external sources, and so on. Each such contribution, though, was seen as potentially identifiable and avoidable. With visual observations, on the other hand, there seemed to be hidden contributions to error that could not easily be evaluated: a judgement of brightness that might be influenced by the observer's alertness, visual characteristics or unwitting bias. At the root of the comparison was an unsubstantiated faith in physical measurement and a distrust of physiologically-based perception.

To physical scientists by the early twentieth century, the need to consider explicitly the condition of the observer along with the experiment itself had become distasteful. According to the physicists Richtmeyer and Crittenden:

> the question of the precision of photometric measurements is of peculiar importance in that in this field, more than any other, the precision obtainable is limited by other than physical factors; namely, by the ability of the eye to decide when two adjacent areas appear equally bright.[211]

These 'other than physical factors' had to be avoided. Practitioners such as Richtmeyer sought something better than visual photometry. The solution, they believed, lay in physical methods. Early summarisers of the photometric state-of-the-art noted the trend away from visual measurement and towards 'physical' methods, even if they were pessimistic about the current success:

> As a department of physical science the subject does not seem to have been very attractive, probably because it is one of the least accurate kinds of measurement. Many attempts have been made to banish visual photometry altogether from the physical laboratory. At one time it was thought that the radiometer would supplant it, but it was soon found that the rotation of the "light mill" depended on thermal rather than on luminous rays. The thermopile and the bolometer have been used to measure the whole radiant energy by means of electrical apparatus, and the dark rays or the luminous rays have been filtered out by selective absorption. Considerable accuracy is possible with such methods, but even if by great precautions changes of temperature have been avoided, and unsuspected radiation of heat guarded

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[211] F. K. Richtmeyer and E. C. Crittenden, 'The precision of photometric measurements', *JOSA & RSI* 4 (1920), 371-87. This sentiment was echoed in a practical context: 'The existence of these phenomena [glare, etc.] affords one reason why illuminating engineering differs radically from most other fields of engineering. The ultimate judgement. . . must be based on an appeal to the senses' [J. Teichmuller, *Illum. Eng.* 21 (1928), 130].

> against, the proportion of luminous energy to thermal energy is so small that it is hopeless to arrive at any precise measurement of light alone.[212]

The practicalities of using a radiometric detector to measure visible light were indeed onerous. The 'great precautions' needed to avoid swamping the small visible contribution to radiant heating proved impracticable.

Addressing a meeting of the Illuminating Engineering Society of New York, it was left to an engineer to express their growing desire for a *quantitative* subject:

> All the natural sciences aim, then, at becoming exact sciences and become exact through the making, correlation and reduction of measurements. Any branch of natural science without measurements is not above the qualitative stage. The number and degree of precision of the measurements in a branch of science is a gage of the extent to which that branch has become exact.[213]

The latter half of the nineteenth century thus saw photometry reconceived as a useful tool, particularly by astronomers and engineers. The stimulus for this revised perception was, in each case, *utility*. Astronomers and spectroscopists saw photometry as a means of extending their grasp and of uniting their studies with those of an increasingly mathematised physical science. Gas and electric lighting engineers exploited it as a tool to regularise production and to gain commercial advantage. Standards of stellar magnitude and luminous intensity conferred legitimacy on the subject and promoted its expansion. With its rising application, however, the practitioners of photometry became increasingly aware of the technical weaknesses of visual methods; their enthusiasm to use photometry was tempered by dissatisfaction with its practical difficulties. The scientists elaborated strategies to minimise the effect of the observer and experimented with photographic methods, while the engineers employed visual techniques, which alone could provide a direct measure of the sensation of illumination at a speed adequate for routine work. The development of the subject over the following decades, however, relied more upon its perceived utility for the emerging communities than on improvements in its foundations or practice.

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[212]A. P. Trotter, *op. cit.*, 68.

[213]A. E. Kennelly, *Trans. Illum. Eng. Soc. (NY)* 6 (1911), 580.

Chapter 4

The Organisation of Light Measurement

In contrast to the preceding chapters which cited a number of isolated cases in an ill-defined field, this chapter adopts a more focused perspective. In so doing, it mirrors the emergence of the subject of photometry itself.

The measurement of light intensity was becoming an increasingly organised activity at the close of the nineteenth century. Photometry was an agent in the 'era of technological enthusiasm' cogently described by Thomas Hughes, during which new technological networks were actively constructed.[214] Promoting the new cultural values of quantification, standardisation and control were new groups of career workers. This chapter examines the 'professional' alliances that increasingly brought together these practitioners (although they generally eschewed the idea of a profession *per se*).[215]

Between the late nineteenth and early twentieth centuries, the measurement of light intensity was carried out in various *milieux* and by a variety of people. While the predominant users of photometry continued to be relatively unskilled inspectors, those responsible for the principal innovations in practice and technology changed during the period. These latter ranged from enthusiasts and amateurs during the nineteenth century to the well-connected and influential career scientists active shortly before the Second World War. In Britain, at least, the subject of light measurement was profoundly shaped by individuals, both acting alone and giving purposeful

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[214] T. P. Hughes, *American Genesis: a Century of Invention and Technological Enthusiasm* (N.Y., 1989).

[215] Their goal was, rather, what has been called 'occupational upgrading' instead of 'professionalisation' [J. B. Morrell, 'Science in the universities: some reconsiderations', in: T. Frängsmyr (ed.), *Solomon's House Revisited: the Organization and Institutionalization of Science* (Canton, MA, 1990), 51-64]. For a discussion of the changing sociological definitions of professionalisation and bureaucratisation, see R. Torstendahl, 'Engineers in industry 1850-1910: professional men and new bureaucrats. A comparative approach', in: C. G. Bernhard *et al.*, *Science, Technology and Society in the Time of Alfred Nobel* (Oxford, 1982), 253-70.

direction to fledgling organisations. Britain was also the country exhibiting the greatest range of organisations involved with photometry in the first decades of the century. This chapter therefore illustrates the organisation of its practitioners by focusing on the careers of several Britons.

At least two social groupings of practitioners became established: engineers concerned with lighting technology, and a loose collection of scientists active in applied optics and instrumentation. By the end of the First World War, these communities increasingly were characterised by a growing self-awareness, identification of common aims, establishment of training programmes and interaction with other organisations. Technical societies united individuals active in the subject before other forms of organisation became significant. Two other significant aspects of the growing social networks are given attention in later chapters. Chapter 5 deals with the direct employment of practitioners by government and industry, and Chapter 7 with the rise in importance of delegated bodies.

Amateurs and independent research

The subject of photometry, peripheral to much of nineteenth century science, was sustained by enthusiastic amateurs, a scientific type prevalent in Britain.[216] By championing an unpopular subject using private funds, they were able to both increase its exposure to particular communities and to nurture its development along individualistic lines.

William de Wiveleslie Abney (1843-1920) typifies the career pattern of a particularly dedicated nineteenth-century exponent of light measurement. Obtaining a commission to the Royal Engineers at the age of 18, he spent a decade in India. Invalided home in 1871, he was appointed as chemical assistant to the instructor of telegraphy at the Chatham school of military engineering, where he was able to pursue a boyhood interest in photography. Within three years Abney was responsible

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[216] D. S. L. Cardwell has discussed reasons for the British condition of 'scientific amateurism' which persisted until the turn of the twentieth century, ascribing it to the lack of a system of academic posts and of government commitment to funding scientific education and applied research. See *The Organisation of Science in England* (London, 1972), 179-84.

for a separate school of chemistry and photography there, and became Inspector of School Science at the Science and Art Department located at South Kensington. His career after this time was devoted equally to education and science. Abney retired from the army in 1881.[217] In the same year, he introduced the first sensitive photographic emulsion based on gelatine. His interests, centring on scientific photography, extended to all matters photometric.

Abney published over 100 papers and a similar number of popular articles on photography, sensitometry, physiological optics and photometry – almost all connected with the measurement or perception of intensity.[218] Editor of *The Photographic Journal* (London) from 1876 until his death, he was a prolific contributor to numerous photographic, astronomical and scientific journals. He was active in scientific and technical societies, being elected president of the Royal Photographic Society four times between 1892 and 1905, president of the Astronomical Society from 1893 to 1895, and of the Physical Society between 1895 and 1897. For Abney, light measurement was an essential adjunct to scientific photography. He lamented that 'of 25,000 people who took photographs not more than one cared for, or knew anything about, the why and wherefore'.[219] With missionary zeal, Abney sought to convert the lack of scientific interest regarding

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[217]Abney's career, mixing service in the Royal Engineers with science teaching, was typical of the period. By the early 1870s, a lack of science teachers caused the War Office to allow officers of the Royal Engineers to supervise examinations of the Department of Science and Art. Abney told an 1881 Royal Commission 'the training and education of engineer officers renders them fit persons to be acting inspectors [of science classes]'. See Cardwell, *op. cit.*, 116, 136. He did not *share* the two roles, however: the War Office was informed in 1878 that his recall to his Corps would 'inconvenience the public service' [Departmental Minutes, quoted in H. Butterworth, *The Science and Art Department, 1853-1900* (PhD thesis, Univ. Sheffield, 1968), 100].

[218]In deciding to promote him, his superior wrote in 1884 that he was 'never very sure of Abney, who had a strong liking for putting his name on original work'. Abney eventually succeeded him as Director of Science, and when the Department was reorganised in 1900 became 'Principal Assistant Secretary, Science and Art Dept.' and finally 'Head of the South Kensington branch of the Board'. He retired in 1903 but had continued contact with the Department almost until his death. See *ibid.*, 479.

[219]Obituary notice: *Proc. Roy. Soc.* A99 (1921), i-v. Other biographical sources: *DNB* (1912-21), 1; *DSB* 1, 21-2 and Butterworth, *op. cit.*

photometric issues. During his presidency of the London Photographic Society in the 1890s, he transformed it into a scientific institution, prompting one commentator to remark that 'the meetings became still duller, and *The Photographic Journal* was devoted almost exclusively to scientific aspects of photography'.[220]

Abney was central in setting foundations for photographic photometry and unique in having a broad interest in light measurement as well as an almost unparalleled desire (for his time) to understand the scientific basis of photography. The connection was not easy to popularise. 'The idea of measuring light is so unfamiliar to many quite intelligent people, that they confuse the word photometry with photography, and have neither the remotest idea that light can be measured nor how any operation of measurement can be carried out when no units of length, volume, weight. . . or time, or appreciable force or movement, enter into the question', complained one of his contemporaries.[221] Abney and his occasional collaborators studied the light sensitivity of photographic materials as a function of chemistry, wavelength of light and processing conditions.[222] He used photographic methods to explore subjects as diverse as the intensity of coronal light during a solar eclipse,[223] the spectrum of electric lamps,[224] the near-infrared spectrum,[225] and

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[220]H. Gernsheim, *The History of Photography* (Oxford, 1955), 256. Regarding the limited attention given to scientific investigation in the photographic industry, see D. E. H. Edgerton, 'Industrial research in the British photographic industry, 1879-1939', in: J. Liebenau, *The Challenge of New Technology* (Aldershot, 1988), 106-34.

[221]A. P. Trotter, *Illumination: Its Distribution and Measurement* (London, 1911), 65.

[222]W. de W. Abney, 'On the opacity of the developed photographic image', *Phil. Mag.* (4th series) 48 (1874), 161-5.

[223]W. Abney and T. E. Thorpe, 'On the determination of the photometric intensity of the coronal light during the solar eclipse of August 28-29, 1886', *Proc. Roy. Soc.* 44 (1886), 392.

[224]W. Abney and E. R. Festing, 'The relation between electric energy and radiation in the spectrum of incandescence lamps', *Proc. Roy. Soc.* 37, 157. Festing knew Abney both during their time as Royal Engineers and later in his role as keeper of the Science Collection at South Kensington.

numerous other topics of contemporary interest. Abney's contributions to photographic sensitometry, in particular, were much cited in contemporary texts. Drawing on his educational connections, he gave courses of public lectures on photography and colorimetry (both of which led to popular books). Abney's cross-fertilisation of astronomy, physiology, photography and physics may well have introduced many of his scientific contemporaries to photometric approaches of investigation.

In a period when full-time scientific employment was still uncommon in Britain, William Abney was nevertheless more than the modern definition of an amateur. His investigations were careful and extensive, maintaining close connections with professional scientists. On the other hand, his researches were usually divorced from the duties of his paid position, and he was active in several associations more closely linked with enthusiasts than to men of science. Apart from monetary remuneration, however, Abney was in most respects a career scientist.

Abney's research and occupational history were by no means unique. One of his near contemporaries, J. Norman Lockyer (1836-1920), followed a similar career path in several respects.[226] Lockyer took up astronomy as a hobby while working as a clerk in the British War Office. His first observatory was set up in his garden at Wimbledon in 1862. Noting his interests, Lockyer's superiors assigned him to a succession of posts relating to scientific administration. These were followed by a grant for equipment to observe the 1868 eclipse, directorship of the Solar Physics Observatory which opened in South Kensington in 1879, and a professorship at the Royal College of Science in 1881.[227] He founded the journal *Nature* in 1869, editing it for fifty years, and was president of the British Association for the Advancement of Science in 1903. In the latter two roles, he promoted the widespread application of

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[225]W. Abney, 'On the photographic method of mapping the least refrangible rays of the solar spectrum', *Proc. Roy. Soc.* 30, 67, and 'On the limit of the visibility of the different rays of the spectrum', *Astron. & Astrophys.* 11 (1892), 296-305.

[226]See, for example, J. B. Hearnshaw, *The Analysis of Starlight: One Hundred and Fifty Years of Stellar Spectroscopy* (Cambridge, 1986), 89-94 and *DSB* 8, 440-3.

[227]The publication of science books was also a significant source of his income. See W. H. Brock, 'The spectrum of science patronage', in: G. L'E. Turner (ed.), *The Patronage of Science in the Nineteenth Century* (Leyden, 1976), 199.

science to social problems. By 1890, Lockyer was an influential figure, too, in British spectroscopy, for which he promoted photometric measurement.

Abney and Lockyer were typical of British investigators in photometry before 1900. Developing a strong amateur interest in a subject neglected by full-time scientists, they engaged in independent research, lobbied for support, and popularised their studies by means of public lectures and books of general interest. The publicising of scientific specialties in this way was an effective method of gaining support in the late Victorian period, when lay-persons could and did read scientific journals and books. Neither Abney nor Lockyer had any success (nor expressed motive) in organising scientists or engineers into special-interest groups. Rather, they attempted to rally other individual investigators to their cause by providing examples of its utility. Thus Abney preferred a cogent demonstration to a meticulous study, illustrating colour blindness by mapping the response of one subject's eyes to colour, for example, rather than by examining a cross-section of individuals. The result of this method of leading by example was that both Abney and Lockyer became respected members and officers of scientific and technical societies, but never founded organisations of their own. Exemplars rather than leaders, their enthusiasms were not, on the whole, shared by their contemporaries, and remained marginalised as minority interests in societies having broader goals.

The technique of mobilising *popular* interest and secondarily entraining *scientific* attention was a tactic also employed by a separate group of individuals intimately concerned with light measurement: the 'illuminating engineers'. In contrast to their seniors Abney and Lockyer, however, the engineers proved remarkably effective in defining both a subject and a career structure for themselves.

Illuminating Engineering in Britain and America[228]

In the first decade of the twentieth century, illuminating engineering was a subject close to attaining a self-recognised career status, yet its practitioners were, for

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[228] 'Illuminating', because, as several of the early engineers complained, the term 'illumination' was more closely associated with mediaeval manuscripts or fireworks than with lighting.

the most part, hesitant to call themselves professionals.[229] Their self-awareness sprouted in the span of scarcely a decade. Besides their impressive rate of growth, the utilitarian origins, too, of the illuminating engineers were quite separate from the more recreational scientific interests of Abney and his generation. Also in marked contrast to their predecessors the gas inspectors, the illuminating engineers promoted the scientific development of light measurement for utilitarian ends.

With the commercial availability of electric lighting in the 1880s, an atmosphere of rapid technological development and 'progress' had become widespread. Bright, steady light became not only a desired utility but a symbol of scientific advancement. The journal *La Lumière Électrique*, for example, founded in 1880, promoted every aspect of electrical technology and devoted a portion of its three yearly volumes to illumination and its measurement. Electricity would indeed supply the light of the future, figuratively as well as literally.

Applying the new technology demanded more than just an engineering bent, however. The electrical enthusiasts who developed lighting systems found themselves faced with marketing, physiological and economic questions. How were they to convince purchasers of the *need* for more or better lighting? How could they compare meaningfully the competing light sources in terms of brightness, colour, and efficiency? How much light *was* needed for various tasks, and how should lighting systems best be installed and employed? Increasingly, the measurement of *illumination* rather than the *luminance* of light sources was emphasised, raising concerns of fair pricing. 'If serious attention is to be given to the often recurring suggestion that the customers of lighting companies be charged according to the actual illumination secured and that street lighting be rated and paid for on a mean or

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[229]The term *profession* defies precise definition. Some of the characteristics commonly ascribed to professionals that the illuminating engineers *lacked*, however, were an educational process, recognition of status by the state and a self-perception of social duty. For a discussion of the 'impressive imprecision' surrounding the definition, see R. A. Buchanan, *The Engineers: A History of the Engineering Profession in Britain 1750-1914* (London, 1989), 12-15. For a good introduction to scientific professionalisation, see J. B. Morrell, 'Professionalisation', in: R. C. Olby *et al.*, *Companion to the History of Modern Science* (London, 1990), 980-9.

a minimum illumination basis', noted one author, 'reliable methods of measurement are indispensable'.[230]

The Illuminating Engineering Society was founded in New York in 1905 by a group of 25 who wanted a society dealing specifically with the art and science of illumination. As was to be mirrored in Britain, the society was preceded by a general-circulation magazine, *The Illuminating Engineer*.[231] Indeed, it appears that these publications preached the sermon of illuminating engineering before a 'common enterprise' was recognised, thereby hastening its advent. The idea was first mooted by Louis B. Marks, a consulting electrical engineer, and Van R. Lansingh, an engineer at the Holophane Glass Co., who decided to contact interested persons, judging that 'six or eight men, if they are the right ones, would do for a starter'.[232] The society gained 93 members in its first year, and within two years the membership had swelled beyond 1000. Early prominent members included Thomas Edison and André Blondel, the principal French exemplar of intensity standards.[233]

Despite its claimed interest in science, the new-born society's practical concerns were decidedly utilitarian. One proposed name was the 'Society for Economical Illumination'.[234] Indeed, the new members frequently stressed *economy* in their early rhetoric.[235] The motivations of this first Illuminating Engineering

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[230]W. E. Wickenden, *Illumination and Photometry* (London, 1910), 72-3.

[231]The editor of *The Illuminating Engineer (NY)*, E. Leavenworth Elliott, became the first secretary of the Society. The magazine retained its independent status, however, with *Trans. Illum. Eng. Soc. (NY)* becoming the Society organ.

[232]S. G. Hibben, 'The Society's first year', *Illuminating Engineering (USA)* (Jan., 1956), 145-52. Marks had patented an enclosed carbon arc lamp as an undergraduate, and later worked for the Westinghouse Electric & Manufacturing company. The Holophane Glass Co., based in New York, specialised in the design and manufacture of novel prismatic lamp globes to control and redirect light, and employed a high proportion of the illuminating engineers of the area.

[233]Data comparing the early memberships of the New York and London societies is given in Appendix IV.

[234]Hibben, *op. cit.* 147.

[235]See, for example, Wickenden, *op. cit.*, Chap. XIV: 'Engineering and economic principles in interior illumination'.

Society centred on the efficient usage of lighting. Its first president observed that lighting costs in the United States in 1905 were conservatively estimated at $200,000,000 per year, of which some $20,000,000 was wasted by the consumer 'by reason of his failure to properly utilise the energy supplied'. This 10% wastage rose to 25%, he continued, 'by improper disposition of light sources or unsuitable equipment of lamps, globes, shades, or reflectors'. The aim of the society was therefore 'to point out in what way the best illuminating result may be obtained from any source of light, be it electric, gas, oil, or candle'.[236] Relatively little mention of light *measurement* appears in its early publications. The 22 papers presented in the first year included two on photometry, both of them presented by British members.[237]

Having branches in five north-eastern cities, the society consciously sought members having a practical, rather than scientific, bent.[238] Their society did not attempt to attract scientists, instead including 'electrical engineers, gas engineers, architects and designers of lighting fixtures' among its members Tellingly, 'the views not only of the engineer but of the practitician will be courted'.[239] Significant support from industry is indicated by the income generated by advertisements in the *Transactions of the Illuminating Engineering Society of New York*.[240]

The birth of a society dedicated to illumination was not welcomed by all. Some preferred that illumination and photometry be made the subject of sub-committees of existing electrical and gas societies. Moreover, it was argued,

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[236]L. B. Marks, 'Inaugural address of the President', *Trans. Illum. Eng. Soc. (NY)* 1 (1906), 7-8.

[237]A. P. Trotter, 'Errors in photometry', and M. Hyde-Cady, 'Lamp photometry', *Trans. Illum. Eng. Soc. (NY)* 1 (1906).

[238]The number of regional chapters increased to 14 during the 1920s, and to 21 by World War II.

[239]Anon., 'The organisation of the Illuminating Engineering Society', *Trans. Illum. Eng. Soc. (NY)* 1 (1906), 2 and 8. Unlike their counterparts in London, the original officers and council of the Illuminating Engineering Society of N.Y. were not closely connected with other developments in American photometry. This chapter therefore focuses on the British organisation.

[240]'Annual Report' *Trans. Illum. Eng. Soc. (NY)* 8 (1913), 683. Advertising for the 1913 fiscal year provided $1097.14, some 13% of total income.

excessive development might make life more difficult for practitioners. One editorialist noted that ‘at present, commercial photometry is delightfully simple, and it is questionable whether anything tending to complicate it will be welcomed by practical men’.[241] Others felt that the subject was intrinsically unworthy of attention: ‘Can illumination be measured with sufficient accuracy and with sufficiently simple apparatus to make it a practical basis for many matters?’[242] The writer concluded that it could not.

The situation in New York had several parallels with that in London. In both cities, competition in lighting systems was increasing, and growing numbers of self-trained specialists were acting as consultants on matters of illumination. Leon Gaster (1852-1928), a British engineer much impressed by this American example, promoted the foundation of a similar society in Britain.[243] He had become editor of a new magazine, *The Illuminating Engineer*, published by the Illuminating Engineering Co., Ltd., in 1908.[244] The publication attracted 140 readers, drawn mainly from engineering and science, by the end of its first year. As with its American counterpart, the magazine also united many of them in a common interest. Writing for newspapers and other periodicals as well as his own, Gaster was a tireless proselytiser for the need of an organisation concerned with illumination. His efforts

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[241]Anon., *Electrician*, Aug. 30, 1907, quoted in *Illum. Eng.* 1 (1908), 144.

[242]Anon., *The Electrical Times*, Dec. 19, 1907, quoted *ibid*.

[243]Gaster was born in Bucharest, and obtained a BSc in 1890. He worked for four years in electrotechnics under E. H. Weber at the Zurich Polytechnic, and moved to the UK in 1895. Gaster became a naturalised British subject in 1903, when he began to do consulting engineering. See ‘Twenty-one years of illuminating engineering’, *Illum. Eng.* 19 (1926), 12. The extent of his connections with the American society are unclear: Gaster had contributed a paper to its first year’s *Transactions*, and was at least in contact with its officers. Although occasionally referred to as ‘sister organisations’, the two societies had no formal connection.

[244]The backers of this company and periodical are unclear, but did not include Gaster himself.

paid off: at a meeting in a Piccadilly restaurant in early 1909, 26 interested individuals founded the Illuminating Engineering Society of London.[245]

These two independent societies collected together a highly eclectic assortment of individuals interested in the practice and measurement of illumination. Unlike the economic and practical motives of the American society, however, the British version was to centre on scientific measurement and application.[246] Subtitling the magazine *The Journal of Scientific Illumination*, its editor strove to promote this orientation. At the founding meeting and in editorials, the London society made clear its objectives and laid emphasis on quantitative measurement. 'What is wanted, above all, is to make the measurement of illumination a practical and familiar practice', wrote Gaster, 'just as the measurement of electric current or gas is already felt to be'.[247]

The 'Illuminating Engineering movement' (so-called by the founders on both sides of the Atlantic) was an uneasy collection of groups with narrower interests. Indeed, the titling of the periodical *The Illuminating Engineer* was a provocative attempt to define a hitherto non-existent community, because no such occupational identity was recognised even among practitioners. The society would encourage the co-operation 'of oculists, physicists, the optical industry, architectural profession and Society of Engineers in Charge'. There were, however, existing animosities to be overcome. One of the proposers noted that 'the bringing together of those

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[245]The German equivalent, the Beleuchtungstechnische Gesellschaft (Society for Illumination Technology) was founded in 1912 by the then director of the PTR, Emil Warburg. Its tardy formation may be attributable to the dominance of the Reichsanstalt in setting industrial standards and in centralising action on questions of illumination and measurement. Illuminating engineering societies were organised later in several other countries: Japan in 1917, Austria in 1924; and Holland in 1926. Even in the USSR, which was less influenced by market forces, societies and research labs sprang up: in Leningrad in 1923, Moscow 1927, and Kharkov in 1929.

[246]The relative importance of British versus American scientists in 'authenticating' the new electrical technology at the turn of the century is discussed in T. P. Hughes, *Networks of Power* (Baltimore, 1983), 53 and 234.

[247]L. Gaster, 'Editorial', *Illum. Eng.* 2 (1909), 796.

representing gas, electricity &c. was a stupendous task'. The previous year, Gaster had written on this topic:

> At the time of his inception the illuminating engineer was hailed as a man likely to add to the gaiety of nations. It was freely prophesied, owing to the conflicting interests of electricity, oil, and gas, that a meeting of an illuminating society would have more the aspect of a beer garden than a sedate scientific assembly. . . but, as is often the case, the prophets have turned out to be windbags and the illuminating engineer, at least in America, is an established fact.[248]

Gaster was repeatedly to stress the *neutrality* of the journal and Society in questions of technological evaluation. Nor were the divisions restricted to engineers backing competing technologies. The disparate concerns of physiologists and engineers were remarked by an oculist: 'some attention has been paid to the subject [of the physiological effect of light] by the medical profession, but their views were not sufficiently impressed upon the engineers.'[249] In an activity so new, the range of illuminating engineering itself was not yet circumscribed. Kenelm Edgcumbe, an instrument-maker, gave examples of the measurement of illumination later used for courtroom evidence, 'one illustration of the unexpected directions in which the need for light measurement was constantly being experienced'.[250]

Despite Gaster's strenuous efforts to found the new society, he willingly accepted the position of Secretary and proposed a noted scientist as President. This served the dual purpose of linking the society to science and giving it a prominent figurehead. The founders sought 'one who is in sympathy with our movement and has taken a wide interest in light, illumination and illuminants generally'.[251] Rather than a scientific enthusiast like William Abney, they sought an established scientist

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[248]L. Gaster, 'The illuminating engineer as specialist', *Illum. Eng.* 1 (1908), 175-7.

[249]H. Parsons, *Illum. Eng.* 2 (1909), 156.

[250]Kenelm Edgcumbe was co-director of Everett, Edgcumbe & Co., a firm specialising in the manufacture of optical instruments, particularly photometers. He was in later years a member and President of the British National Committee on Illumination, a delegate to the Commission Internationale de l'Éclairage, and chairman of the British Engineering Standards Association, in which capacity he set specifications for photometric instruments.

[251]J. S. & H. G. Thompson, *Silvanus Phillips Thompson: his Life and Letters* (London, 1920), 274.

having industrial connections, someone who had made the subject his *business*. They found their man in Silvanus Phillips Thompson. Thompson (1851-1915) was a well-known and respected populariser of science and educator. His career until then had concentrated on electrical engineering and technical physics, having chaired the Research Committee of the Institute of Electrical Engineers, and been its President in 1899. During the 1890s he had researched *x*-rays and fluorescence and developed an interest in photometry, leading to the short work *Notes on Photometry* in 1893.[252]

One of Thompson's acquaintances, the Engineer-in-Chief of the Post Office, William Preece, shared some of the qualities required of a candidate for leadership of the Illuminating Engineering Society. In 1893 he had organised a committee in England to act with a similar group in America to consider a standard of light and illumination. Preece had already been interested in photometry for over a decade, having been asked by the Commissioners of Sewers of the City of London in 1883 to prepare a specification for lighting part of the City by electricity, and granted a sum of £200 by them for experiments.[253]

Some ten years before the formation of the Illuminating Engineering Society, then, Preece had asked Thompson, along with William Abney and John Fleming, to serve on his committee.[254] Thompson, in turn, approached his acquaintance Hermann von Helmholtz, director of the new national laboratory, the Physikalisch-Technische Reichsanstalt, about German participation. As will be discussed in Chapter 5, the Reichsanstalt was just completing research on a fundamental standard of light, and felt little inclination to work with ill-prepared collaborators. Nothing came of the

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[252]Thompson had considerable assistance in writing his *Notes on Photometry* from his friend Alexander Trotter, a London consulting engineer who supplied him with information on 'the very latest thing in photometers and photometry'. See Thompson, *op. cit.*, 256. Trotter had also assisted William Preece in 1883-4 with his measurements on illumination. See also footnote [71].

[253]J. W. T. Walsh, 'The early years of illuminating engineering in Great Britain', *Trans. Illum. Eng. Soc.* 16 (1951), 49-60.

[254]Thompson, *op. cit.*, 273. John Ambrose Fleming (1849-1945) had been a consultant to the Edison Electrical Light Co. from 1881 to 1885, and was professor of Electrotechnology at University College, London, for 41 years. His text on laboratory methods, published in 1907, included a chapter on photometry.

committee other than Thompson's heightened profile both at home and abroad as an expert on photometry.[255]

Barely eight years younger than William Abney, Thompson nevertheless followed a career path more effectively tuned to exploiting his subject in a rapidly changing society. Besides being a populariser of science, Thompson was a promoter of better education and industrial links. In 1902 he began a campaign to organise an institute of 'opto-technics' (in analogy to the 'electrotechnical' training courses then becoming widely available). Elected President of the Optical Society in 1905, he organised the first Optical Convention at the sole British institution teaching technical optics, the Northampton Institute in London.[256] The Convention exhibited the work of the optical trades, which according to Thompson employed some 20,000 workers in the London district alone.[257]

With his background in electrotechnics and optics and his high public profile, Thompson proved an effective figurehead for the new Illuminating Engineering Society. He was vocal in his opinions about the current status of photometry and lighting: 'the ascertained facts are few – all too few; their significance is immense; their economics and social value great; but the ignorance respecting them generally is colossal! . . . To sum up, the work before us is *to diffuse the light*'.[258] During the four years of his presidency, Thompson promoted the Society and its governmental and international connections, continuing until shortly before his death in 1915.[259]

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[255]His Christmas Lecture of 1896 on 'Light visible and invisible' was translated into German by Otto Lummer of the Optics Section of the PTR.

[256]For a discussion of its later-developing French counterpart, l'Institut d'Optique, see H. W. Paul, *From Knowledge to Power: the Rise of the Science Empire in France, 1860-1939* (Cambridge, 1985), 310-3.

[257]Thompson, *op. cit.*, 264.

[258]*Ibid.*, 275, quoting from Thompson's 1909 inaugural lecture as President of the IES (London).

[259]In 1912, for example, he chaired a meeting of the London society and its American counterpart at the National Physical Laboratory to discuss photometric nomenclature.

The choice of President and Secretary was instrumental in crystallising the goals and outlook of the Society and its members. The early publications mirrored the new society’s self-perception. The founding members were not eager to claim professional status. Indeed, the very idea of illuminating engineering as a *profession* was actively derided. Leon Gaster noted that

> membership of such a society cannot, at the present time, be regarded as any claim to professional distinction. We naturally hope that in times to come, when the subject of illumination has been thrashed out in detail to a far greater extent than at present, “expert illuminating engineers” will have a professional existence and will, even though few in number, be entitled to claim the distinction that the name implies. . . the number of experts in this country who are entitled to claim the title with any approach to justice are. . . few indeed.

The society was to be called not *The Society of Illuminating Engineers* but *The Illuminating Engineering Society*. ‘This meant anyone interested in the subject of lighting could join the society but membership would not carry with it any professional status’.[260] The American society had agreed to a similar name for similar reasons; in both cases, the proposal for the name Illuminating Engineering Society prevailed, making it ‘representative of an art’ instead ‘of a profession’.[261] In another editorial, Gaster again cautioned against defining arbitrarily the profession of illuminating engineer: ‘any attempt to force his existence in name only, without the necessary qualifications, can only bring the title into disrepute’.[262] Both Leon Gaster and Silvanus Thompson voiced their desire to make the society a collection of non-professionals interacting like the participants at meetings of the British Association for the Advancement of Science. This tactic clearly had two benefits: it broadened the potential membership, allying the subject with more established fields; and, it promoted the synthesis of a new subject from components of the old. Gaster’s co-founders agreed with his aims. One, seconding the motion to form the society, replied that he was ‘much impressed of the responsibility in replying on behalf of a

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[260]L. Gaster, *Illum. Eng.* 2 (1909), 156.

[261]Anon., ‘Organization of the Illuminating Engineering Society’, *Trans. Illum. Eng. Soc. (NY)* 1 (1906), 1.

[262]The desire among electrotechnicians and other engineers to replace unformalised knowledge by higher education in the 1880-1910 period is discussed in Torstendahl, *op. cit* [2].

profession which [does] not yet exist'.[263] Yet as the first president of the society, Silvanus Thompson held a much looser and all-encompassing definition of their activities, stating that 'diverse and individual interests centre upon a common topic

. . . *illumination engineering* [sic]. So far as this is their profession they are engineers – for is not the definition of engineering the art of directing the powers of Nature to the use and convenience of man?' The magazine and society were nevertheless directed at a specific audience, namely the Illuminating Engineering movement:

> In their movement, as in every movement, they must have a number of leaders before an appeal can be made to the masses. [Gaster] had, therefore, endeavoured in the journal to appeal to the scientists and to the better educated engineers, so that once there was agreement as to the necessity of spreading the knowledge of illumination, the public, who were the consumers, would gradually be educated by those pioneers who at the present formed the bulk of the readers of our magazine.[264]

The conscious rejection of professional status by illumination engineers hinged on their recognised lack of qualifications or testing standards. While a few lectures were available, formal training was non-existent.[265] A physicist at Cornell University, F. K. Richtmyer, noted that photometry played a minor role in the education of physicists and engineers. 'Typically the photometrical measurements are only secondary,' he remarked, 'the main point of the experiment being usually the study of some problem by the aid of photometry'. With so little formal training 'it would be presumptuous. . . to regard illuminating engineering as a separate entity in the great science of engineering'.[266] As a partial solution, he proposed a course of ten

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[263]J. S. Dow, *Illum. Eng.* 2 (1909), 158.

[264]*Ibid.*, p. 155.

[265]This contrasts with the teaching standards of electrotechnics established by this time. See G. Gooday, 'Teaching telegraphy and electrotechnics in the physics laboratory: William Ayrton and the creation of an academic space for electrical engineering in Britain 1873-1884', *Hist. Technol.* 13 (1991), 73-111.

[266]F. K. Richtmyer, *Illum. Eng.* 2 (1909), 851-2. Richtmyer (1881-1939) was active in early research into the photoelectric effect and its application to photometry. See, for example, 'Photoelectric cells in photometry', *Trans. Illum. Eng. Soc. (NY)* 8, (1913), 459-69. He was also a promoter of purely photometric research in America, editing the text *Measurement of Radiant Energy* (N.Y., 1937). See H. E. Ives, 'Floyd Karker Richtmyer', *Biog. Mem. Nat. Acad. Sci.* 22 (1943), 71-82.

lectures for his students. The following year, the journal reported on a more elaborate course given at Johns Hopkins University in Baltimore. Thirty-six lectures were given, along with demonstrations and laboratory work, to 250 post-graduate teachers and other interested persons. A more permanent educational facility was set up at the Case School of Applied Science in 1916, which continued to give courses on illuminating engineering through the 1920s.[267] Unlike the academic courses provided for the older engineering specialties, such courses, presented in large part by the illuminating engineering staffs of large firms, presented a business-oriented view of the subject.[268] The Illuminating Engineering Society of New York, too, devoted attention to educational activities. An *Illumination Primer* was published in 1912, and other pamphlets and teaching materials were frequently produced for local chapters of the Society. Lectures were even published in book form.[269] In Britain, similarly, courses on illumination became more common after *The Illuminating Engineer* was launched. As early as 1908, lectures on illumination were held at two London technical institutes: the Northampton Polytechnic and the East London College, followed in 1909 by four Cantor lectures by Leon Gaster at the Royal Society of Arts during the month that the Illuminating Engineering Society was

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[267]The Case School courses were prepared principally by the staff of the Nela Research Laboratory (described in Chap. 5). The two-term course for electrical engineering students covered 'all aspects of illuminating engineering as presently understood' in three lectures per week and laboratory work using Nela equipment. Lecturers included 3 Nela employees, five from the National Lamp Works of GE, an architect, and representatives of two gas lamp manufacturers. See 'Illuminating Engineering for Students and Engineers', *J. Sci. Instr.* 2 (1925), 365-7 and F. E. Cady, 'A cooperative college course in illuminating engineering', *JOSA* 4 (1920), 537-9.

[268]The training situation in illuminating engineering had parallels with that in chemical engineering, a specialty that emerged in the inter-war period. See C. Divall, 'Education for design and production: professional organisation, employers, and the study of chemical engineering in British universities, 1922-1976', *Technol. & Culture* 35 (1994), 258-88.

[269]Illuminating Engineering Society, *Lectures on Illuminating Engineering, Delivered at the Johns Hopkins University October and November 1910* (Baltimore, 1911), and *Illuminating Engineering Practice: Lectures on Illuminating Engineering Delivered at the University of Pennsylvania, Philadelphia, September 20 to 28, 1916* (N.Y., 1917). The former included Charles Steinmetz and Willis Whitney of General Electric as lecturers.

founded, and two years later at three London polytechnics.[270] The availability of the journal and lectures clearly promoted the formation of the society. The lighting industry played a major role in organising courses, The Electric Lamp Manufacturers Association (ELMA), for example, holding annual series of lectures beginning in 1918.[271] In 1926 this educational drive was extended by a 'Home Lighting Course for Women', which included six lectures which were to 'take the audience by easy stages through the history of lighting, illustrating the demands of modern civilisation, and then explain, by the aid of numerous demonstrations, how the home should be wired and lighted'.[272] Despite such attempts by business and technical societies to instigate standards of training for practitioners and support increased awareness among the public, as late as 1936 one commentator was able to state that 'illuminating engineering still remains more of a trade than true profession'.[273]

In spite of a reticence for claims to professionalism by both the British and American societies, by 1910 a well-developed culture of illuminating engineering was established. The diffusion of state-of-the art knowledge is well illustrated by texts independently published by persons associated with the Illuminating Engineering Society of London around this time.[274] A spate of books appeared before the First World War in response to the growing organisation of illuminating engineers. While discussing gas lighting, they generally sought to incorporate illumination and photometry into electrical engineering practice. Hermann Bohle, a South African

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[270] Walsh, *op. cit.*, 53. In 1911, members of the Illuminating Engineering Society of London gave four courses, consisting of a total of 27 lectures.

[271] In America, the National Electric Light Association was similarly occupied with 'propaganda lectures on illumination'. Equivalent organisations in France, Holland and Germany promoted public education regarding the benefits of good lighting.

[272] Anon., *Illum. Eng.* 19 (1926), 144.

[273] P. Moon, *The Scientific Basis of Illuminating Engineering* (N.Y., 1936), 1.

[274] These include: J. A. Fleming, *A Handbook for the Electrical Laboratory and Testing Room, Vol II.* (London, 1907), Chap 3; A. P. Trotter, *Illumination: its distribution and measurement* (London, 1911); H. Bohle, *Electrical Photometry and Illumination* (London, 1912); L. Bell, *The Art of Illumination* (London, 1912); and, A. Blok, *The Elementary Principles of Illumination and Artificial Lighting* (London, 1914).

practitioner, argued that photometry had previously been neglected, ‘yet this subject is as important as, or even more important than, the design of dynamos and motors. It is useless to raise the efficiency of generators and motors by 1 or 2 per cent and afterwards to waste the power by improper illumination engineering’.[275] The practitioners saw themselves as more than merely engineers of economy, however. The current president of the British society emphasised the multidisciplinary nature of his craft, writing: ‘Illumination is not an exact science with well defined laws of what might be called illuminative engineering, but an art whereto an indefinable and incommunicable skill pertains almost as it does to the magic of a painter’.[276]

The domain of the illuminating engineer indeed encompassed disparate skills. He was versed in lamp technology at a time when several systems were commercially viable. Between 1880 and 1920, at least three technologies vied for dominance:

(a) gas lighting, revitalised by efficient burners, incandescent mantles, and high-pressure operation; (b) filament electrical lighting; and (c) arc lamps, for high-intensity lighting of public places. New, more reliable and economical systems were constantly being developed, such as the Nernst glower lamp.[277] Between 1890 and

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[275]H. Bohle, *Electrical Photometry and Illumination* (London, 1912), v. This argument closely parallels an example given by the president of the New York society six years earlier: ‘The electrical engineer goes to great lengths to gain a small percentage in the economy of his boilers, engines, generators and transmitting system; the illuminating engineer has a problem which is in many ways far easier, because he can take the bad conditions which prevail at the present time and can produce a much more considerable betterment in results than lies within the easy reach of the electrical engineer. . . it is very possible to gain very considerable economies quite as useful as the additional economies which are to be attained at the generating plant’. [Marks, *op. cit.*, 11].

[276]L. Bell, *The Art of Illumination* (London, 1912), 336.

[277]Invented by the chemist Hermann Walther Nernst (1864-1941), the lamp consisted of a solid bar of cerium oxide, and later zirconia and yttria, initially heated by an external heater to reduce its resistance and then to incandescence by a controlled electric current. It was about twice as efficient as the contemporary carbon filament lamp (requiring about 2 watts to yield a candlepower of intensity), but proved only about half as efficient as the newer metal filament lamps which overtook it commercially. Another commercial disadvantage was the 10 to 60 seconds required for it to reach incandescence. See, for example, Anon., ‘A new high efficiency Nernst lamp’, *Illum. Eng.* 2 (1909), 351, and K. Mendelssohn,

1910, the difficulties of incandescent lamp manufacture, and potential profits from more efficient technologies, motivated engineers to seek alternatives. During this twenty year period, both innovation and technical development blossomed. The great illuminating efficiency of the firefly was much discussed, and an electrochemical or luminescent analogue was actively sought.[278] The illuminating engineer required a strong background in electrical engineering to appreciate the best operating conditions for these lamps and their interconnection into electrical networks. The increasingly close association between illuminating engineering and electrical engineering is illustrated by a 1926 advertisement calling for an '*illuminating electrical* engineer'.[279]

Illumination also had a strong component of human physiology. The illuminating engineer worked with detailed tables of appropriate lighting levels, itemised for type of work and buildings.[280] Less tangible qualities such as colour and mixture of natural and artificial lighting were also on the agenda.[281]

The World of Walther Nernst: The Rise and Fall of German Science (London, 1973), 45-7.

[278]The firefly example appears, for example, in S. P. Langley & F. W. Very, 'On the cheapest form of light', *Am. J. Sci* 40 (1890), 97; in S. P. Thompson, *The Manufacture of Light* (London, 1906); in H. E. Ives & W. W. Coblentz, 'The light of the fire-fly', *Illum. Eng.* 3 (1910), 496-8; in W. H. Pickering, 'Photometry of the West Indian firefly', *Nature* 97 (1916), 180; and, in H. E. Ives, 'The firefly as an illuminant', *J. Franklin Inst.* 194 (1922), 212. Coblentz recommended mixing the greenish phosphor produced by the firefly with red and blue phosphors of other insects to yield an efficient white light source. Yet Silvanus Thompson felt compelled to emphasise to its new members that the Illuminating Engineering Society would deal with *quantifiable* matters, and that 'our Society has as little to do with fireworks as with fire-flies' [*Illum. Eng.* 2 (1909), 815].

[279]Anon., *Illum. Eng.* 19 (1926), 154; emphasis added.

[280]Such tables had been empirically determined from the early 1890s using make-shift portable 'illumination' photometers. The recommended office lighting levels increased five-fold over the period: 3-4 foot-candles in 1910 [Sunbeam Incandescent Lamp Co.]; 4-8 fc [Bulletin 7C, GE Lamp]; 6-12 fc in 1925 [Bulletin 41B, GE Lamp]; and 20 fc in 1935 [C.E. Wietz, ICS 2749A, GE Lamp], and rose by another factor of five by 1959 [IES Lighting Handbook, 3rd ed.].

[281]E.g. C. E. Clewell, *Factory Lighting* (NY, 1913).

Most pertinently to this thesis, the illuminating engineer worked routinely with photometry, both in a practical and theoretical sense; it formed the sole experimental tool at his disposal and theoretical model of his handiwork. This new community of practitioners rapidly became the principal vector of innovation, application and promulgation of photometry. As with gas inspection some decades earlier, technology and industry were closely linked. The characteristics of commercially available light sources increasingly were measured and tested in commercial production.[282] Numerous portable photometers were available by 1910, designed for either measuring the intensity of a light source or the illumination of a surface.[283] Unusually among his contemporaries, William Preece had in the 1880s urged the measurement of illuminated *surfaces* rather than of light sources themselves. In a paper presented to the Royal Society, he said:

> We do not want to know so much the intensity of the light emitted by a lamp, as the intensity of the illumination of the surface of the book we are reading, or of the paper on which we are writing, or of the walls upon which we hang our pictures, or of the surface of the streets and of the pavements upon which the busy traffic of cities circulates. . . Hence, I propose to measure the illumination of surfaces quite independent of the sources of light by which they are illuminated.[284]

This shifted emphasis was to preoccupy the illuminating engineers and, somewhat later, investigators at government and industrial laboratories.

The growth of the 'illuminating engineering movement' in the first decade of the twentieth century thus entrained technological and social change, and united a disparate collection of workers. These practitioners, seeking to specialise in what appeared to be a readily exploitable subject, began an active dialogue in their journals discussing all aspects of illumination and its measurement. Their expansion was attributable to a combination of practical need and scientific acceptance of an increasingly quantitative subject. One post-WWI practitioner commented that 'the

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[282] J. S. Dow, 'Glow lamp standards and photometry', *Electrician* 57 (1906), 855-7.

[283] Early portable illumination photometers measured the illumination in rooms or lighted streets by an extinction method, in which the operator sighted the illuminated scene and interposed graduated absorbers until it disappeared.

[284] W. H. Preece, 'On a new standard of illumination and the measurement of light', *Proc. Roy. Soc.* 36 (1883), 270-5. The first 'illumination photometer' was constructed by Preece and Trotter at this time.

rapid development of the lighting art, and its transference from the domain of pure empiricism to that of scientific method which has been a marked feature of the last decade of engineering progress, have tended to emphasise more and more the importance of this branch of photometric practice'.[285] The impetus that had been given to photometry over the previous half-century by gas lighting was now virtually spent. Electrotechnology promised to be the technology of the future for lighting and for light measurement. In turn, the emphasis on lighting applications caused mainstream photometry to develop increasingly in this direction.

When Leon Gaster died in January 1928, twenty years after his journal had started, the subject of illuminating engineering had stabilised. The field had been defined by a generation of practising engineers who had systematised the measurement of light. To mark the occasion, the career scientists and engineers now working in the field paid their tributes to him and to the Illuminating Engineering Society. Alexander Trotter, a past President of the society, eulogised with justification that in founding the journal and Society Gaster had 'had the courage to found in anticipation of a demand, the enthusiasm to develop on scientific lines, the skill to balance between competing interests, and the satisfaction of producing so

[285] J. W. T. Walsh, *Photometry* (London, 1926), 6-7.

Table 2 Organisations devoted to lighting and photometric standards ~1935. Source of data: *Compte Rendu CIE* (1935), 646-7.

Country	Organisation	Members	Founded
Sweden	Swedish Lighting Development Society		
France	La Soçiété Française des Électriciens		
France	L'Association des Ingénieurs de l'Éclairage		
France	Society for the Improvement of Lighting		
Germany	German Lighting Association	400	1912
England	Illuminating Engineering Society	540	1908
England	Association of Public Lighting Engineers	250	
England	National Illumination Committee		1913
Holland	The Netherlands National Committee on Illumination		
Japan	Illuminating Engineering Society of Japan	1400	1917
USA	Illuminating Engineering Society	1350	1905

successful and attractive a form'.[286] Clifford Paterson, the current President, noted that in the early days 'the need for the illuminating engineer was not appreciated and

[286]*Illum. Eng.* 21, 17. Trotter was arguably more influential in the British photometric community even than Gaster. Obtaining a BSc from Cambridge, he articled to an engineering firm where he designed lighting and photometric products. He met William Preece in 1884, and began research in illuminating engineering with him. From that time until his later years, he maintained a 'private home laboratory devoted to photometry'. Trotter was briefly director of a dynamo factory, and then editor of *The Electrician* for five years. From 1899, Trotter served as electrical advisor to the Board of Trade, a capacity he filled for 18 years until his retirement. He also supported the formation of a photometry section at the National Physical Laboratory. See 'Mr. Alexander Pelham Trotter', *Illum. Eng.* 19 (1926), 77.

his *profession* only imperfectly understood'.[287] The members were also agreed on the future of their subject. John Walsh of the National Physical Laboratory echoed that he saw the subject as 'increasing. . . rapidly at present'. Elihu Thomson of General Electric in America even saw signs that illuminating engineering was expanding to encompass all forms of electromagnetic radiation:

> Just at present we find great interest in the production and application of rays which cannot be said to be illuminating, but which are of the same general nature. The usefulness of ultra-violet radiation has been thoroughly demonstrated, if we are permitted to use the term "illumination" in reference to invisible rays. . . it is, indeed, difficult to assign limits to what can be done with this enormous range of wave frequencies, and, so far as illumination itself goes, many of the invisible rays are capable of exciting in special fluorescent materials visible light rays. I feel safe in predicting that the opportunities for usefulness for the *Illuminating Engineer* will not be diminished in the forthcoming twenty years.[288]

By 1935, illuminating engineering societies similar to the American and British examples and devoted almost exclusively to electric lighting were active in several countries. Representatives of the younger German and Dutch illuminating engineering societies applauded the international flavour of the journal, and traced its effect in influencing British legislation. Photometry was, in the early decades, a significant part of such organisations, which were principally tasked with the organisation of standards, education, and commercial promotion of lighting.

Perhaps of most practical importance to a practising engineer, the subject also received recognition among lay-persons. The thirteenth edition of the *Encyclopaedia Britannica* of 1927 included an entry for illuminating engineering, written by Gaster himself.

Optical societies

The linkage of illumination engineering with 'electrotechnology' rather than with optics is attributable to the rapid expansion of electric lighting and the growth of a community of practitioners. By contrast, optics before 1914 involved a collection of

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[287]My italics. Paterson used the term *profession* loosely here, and never attempted to associate the more formal attributes of a profession with this community of engineers.

[288]*Illum. Eng.*21, 19.

disparate and unorganised practitioners much as illuminating engineering had done before the turn of the century. Despite the Optical Conventions of 1905 and 1912 in Britain which attempted to bring together all workers in optics, university scientists and optical craftsmen worked in different and almost mutually exclusive aspects of the field. There was little perception among them of optics being an activity of common interest, or of any potential benefit arising from organisation, until the war changed their views. At that time, government, industry and academia became acutely aware of the predominance of German optics. This was particularly true in Britain and America, which had a dangerous reliance on German instruments and glass. The Department of Scientific and Industrial Research was founded in 1915 because

> many of our industries have since the outbreak of war suffered through our inability to produce at home certain articles and materials required in trade processes, the manufacture of which has become localised abroad, and particularly in Germany, because science has there been more thoroughly and effectively applied to the solution of scientific problems bearing on trade and industry and to the elaboration of economical and improved processes of manufacture.[289]

At the time, the UK was manufacturing less than a quarter of the types of optical glass being made by Germany, and a tenth of requirements of the dyestuffs industry. There was an urgent practical need to design and manufacture optical devices and to develop national expertise in all aspects of optics for the war effort.[290] To organise this, the Department of Scientific and Industrial Research and numerous national committees were set up. During and after the war, the new links that had been formed were maintained by the formation of optical societies. These professional groupings aimed to promote research and manufacture in an atmosphere of increased national awareness. Founded in 1916 principally by a group at Eastman Kodak, the Optical Society of America brought together researchers and engineers concerned with all aspects of optics. This included photometry and colorimetry. Its *Journal of*

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[289]*Scheme for the Organisation and Development of Scientific and Industrial Research* (London, 1915), quoted in H. Melville, *The Department of Scientific and Industrial Research* (London, 1962), 23.

[290]For the war's effect on instrumentation companies, see M. E. W. Williams, *The Precision Makers: a History of the Instruments Industry in Britain and France 1870-1939* (London, 1994), 61-80.

the Optical Society of America and Review of Scientific Instruments became the principal English-language organ for scientific optics in the 1920s. Unlike continental journals, *JOSA* treated a much broader field than simply imaging optics. Along with lens design, it dealt with subjects such as colour measurement and the physical principles of light detectors. In England, the *Journal of Scientific Instruments* (founded in 1923) covered similar subjects, notably electrical and mechanical devices for measurement. Nineteenth century optics was being broadened and redefined in terms of new technology.

The memberships, subjects treated and industrial linkages of the optical societies increased steadily through the 1920s. The economic depression of the following decade, however, caused a slump in the membership and publication rate of the Optical Society of America. Its flat membership rolls through the 1930s belied the number of new and extended activities of optical scientists in research, government and industry begun in that decade.

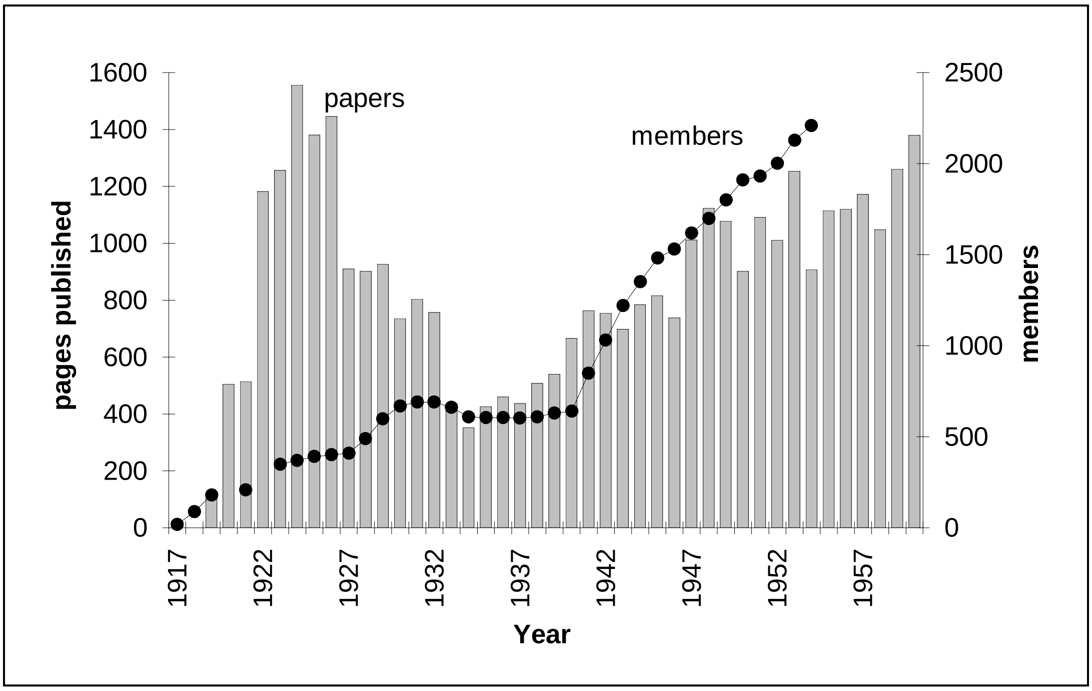

Fig. 9 Growth of the Optical Society of America and its journal. The publication rate for *JOSA* before 1929 was augmented by the co-published *Review of Scientific Instruments*.

The members of the optical societies formed a less homogeneous community than did the illuminating engineers. A major occupation, however, was as scientists in national and industrial laboratories, a subject treated in the next chapter.

This chapter has detailed the transition of photometric innovation from an activity of amateur scientists to career engineers.[291] The turn of the century saw the practice of light measurement appropriated by a new, self-aware community of illuminating engineers that increasingly became allied with the electric lighting industry. Coalescing first in America and Britain, the illuminating engineering movement championed the scientific development of photometry for utilitarian purposes. Optical societies encompassing the subject of light measurement joined in, particularly following the impetus of war-time shortages and organisation, to enlist a broader range of career workers into the problems of light and colour measurement.

While providing a focus for common interests, the movement was ineffectual in carrying out research-oriented activities. Urging photometric standards and measurement practices, they initially had neither the funds nor support needed from government and industry. Instead, the illuminating engineers relied upon a handful of interested scientists using make-shift equipment. The birth of the national and industrial research institutions greatly eased this impasse. Government- and industry-funded laboratories staffed by career scientists were now available, albeit having objectives distinct from those of the illuminating engineering movement. In response to the growing organisation of technical societies, industry and government, the new laboratories were drafted into photometric research, and their employees were brought into the growing community of engineers and scientists concerned with light measurement.

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[291] Appendix V summarises the relationships between early British proponents of photometry.

Chapter 5
Photometry Institutionalised

The opening decades of the twentieth century were a time of rapid transition in light measurement. Self-described illuminating engineers were calling for standards and scientific methods of measurement. The emphasis of photometry shifted from routine gas testing to the measurement of electric lamp intensities and illumination. Visual methods became highly refined, and were joined increasingly by photographic and photoelectric photometry. Light measurement during this period was part of a broader trend towards quantitative methods, standardisation and the growth of science-based industry.[292]

The setting for these changes was a new environment of research and standardising laboratories. National laboratories founded in Germany, Britain and America near the turn of the century, and the industrial laboratories that multiplied after the Great War, deemed light measurement a subject worthy of funding and attention. These new institutions nurtured the transition of photometry from the domain of isolated amateurs and consulting engineers to that of an increasingly influential body of career scientists and engineers – influential in that they affected government policy, international standards and the evolution of industries. The new social locus determined the problems engaged, the methods applied to their solution, and the type of investigator studying them. This chapter describes how these institutions became involved with light measurement, and how their structures influenced their contributions to the subject. Chapter 6 discusses the technological innovations that proceeded in parallel with the organisational evolution of the subject.

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[292]For a broader perspective regarding these cultural changes, see D. F. Noble, *America by Design: Science, Technology and the Rise of Corporate Capitalism* (N.Y., 1979).

The drive of utilitarian need

Before exploring the changing methods and social environment of light measurement engendered by institutions, it is necessary to ask why photometry was transformed from a sideline of a handful of dispersed astronomers and engineers and a tool only of gas inspectors, into a technique of increasing importance that required the establishment of laboratories to exploit it fully. The answer lies in the increasing identification of practical reasons to measure light, coupled with a growing awareness of common aims.

By the end of the nineteenth century, engineers and scientists concerned with photometry agreed on its usefulness but bemoaned its lack of coherency. One text of 1894 described at least thirteen current and proposed illumination standards, with the favourite standard varying from country to country, and industry to town.[293] Methods of photometric measurement were also varied. Some British gas engineers employed a simple variant of Bouguer's photometer, their counterparts in Germany favoured the Bunsen 'grease-spot' instrument, and scientists increasingly used the considerably more precise Lummer-Brodhun device.

The growth of the Illuminating Engineering Movement discussed in Chapter 4 suggests the frustration experienced by individual engineers when faced with the task of designing lighting installations using inadequate concepts and measurement methods. There were, moreover, the concerns raised by the financing of such installations. The electric lighting technology newly available at the turn of the century involved expensive and widespread replacement of gas in public places and industry.[294] The power to control and to dramatically alter lighting was accompanied

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[293]See A. Palaz, *A Treatise on Industrial Photometry, With Special Application to Electric Lighting*, transl. by G. W. & M. R. Patterson (New York, 1894), Chap. 3. Adrien Palaz, born in Switzerland in 1863, studied electrotechnology under E. H. Weber at Zurich Polytechnic. He gained a position at the Bureau Internationale des Poids et Mésures at Sèvres in 1886, and edited the journal *La Lumière Électrique.*

[294]Books on photometry began to emphasise the new illuminants, e.g. ref [2] and W. M. Stine, *Photometrical Measurements and Manual for the General Practice of Photometry, With Special Reference to the Photometry of Arc and Incandescent Lamps* (N.Y., 1900).

by expensive decisions, raising questions concerning the relative efficiency and cost of lighting systems. What *brightness* of illumination was required to write, weave, or assemble products? Doubling the illumination levels in a factory or school could more than double the costs.[295] The *quality* of lighting was also of importance, even if difficult to quantify reliably. Lamp manufacturers such as General Electric in America, Siemens in Germany and Swan in Britain needed to verify the uniformity of the lamps produced. And, to make their products more competitive, they strove to produce as much light as possible from a given power input. Power generating companies, too, had an interest in lighting efficiency: illumination was the primary application of electrical power, and lamp designs could have a dramatic effect on the demands made of new power generating stations.[296] Such questions of adequate illumination, product uniformity and efficiency thus concerned both government and industry. Institutional historian David Cahan has noted how ‘scientists, industrialists and government officials had a common, pressing need to establish trustworthy measures for a score of electrical phenomena’ including ‘the amount of light radiated, the luminous intensity, the energy consumption and light-energy distribution of an illuminating source’.[297] Lighting systems were characterised by high costs of installation, some of which involved large outlays by governments at the local, regional or national level; the costs, in turn, were sensitively dependent on technological developments made by private industry. The granting of contracts for networks of street lighting and other large public works demanded input from impartial technical advisors.

Like the measurement of illumination, interest in the measurement of colour had strong utilitarian motivations. Dye production had expanded dramatically after the development of synthetic dyes in the second half of the nineteenth century. By the turn of the twentieth century dye chemistry was a major industry, accompanied by the

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[295]In Britain, these questions led to influential committee reports by the Departmental Committee on Lighting in Factories and Workshops in 1915, 1921 and 1922.

[296]See Chap. 4, footnote 62.

[297]D. Cahan, *An Institute for an Empire: the Physikalisch-Technische Reichsanstalt 1871-1918* (Cambridge, 1989), 17-8.

growth of research laboratories.[298] In the printing industry, colour printing processes had been much developed and were commonplace by the 1890s. Both of these applications demanded high-quality matching of colours and routine, rapid measurements. The demands from industry for colour standards for dyes and inks required research into the perception of colour, the effects of lighting, lamp characteristics and surface finish.

Such applications also provided great potential and risks for companies, increasingly competing on an international scale.[299] The situation led to a partial merging of government and industrial interests in a new form of institutionalised scientific research: the government standards laboratory.

Photometry was elaborated and systematised on an unprecedented scale at government institutions such as the Physikalisch-Technische Reichsanstalt in Germany, the National Physical Laboratory in England and the National Bureau of Standards in the USA. Each of these institutions was born around the turn of the century: the PTR in 1887, the NPL in 1899, and the NBS in 1901.

The Physikalisch-Technische Reichsanstalt[300]

The Physikalisch-Technische Reichsanstalt (the Imperial Institute of Physics and Technology, henceforth PTR or Reichsanstalt) was founded in Berlin in 1887. Werner Siemens, head of the Berlin electrical firm Siemens & Halske, was a driving force in its foundation, donating land to the Prussian government for a 'state institute in experimental physics' to promote the 'advancement of science and, thereby, also

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[298]E. Homburg, 'The emergence of research laboratories in the dyestuffs industry, 1870-1900', *BJHS* 25 (1992), 91-111.

[299]For an excellent study of the growth of electrical power systems, see T. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore, 1983).

[300]The chief source for this section is D. Cahan, *op. cit.* See also F. Pfetsch, 'Scientific organisation and science policy in imperial Germany, 1871-1914: the foundation of the Imperial Institute of Physics and Technology', *Minerva* 8 (1970), 557-80.

the technology closely bound to it'.[301] Siemens encouraged the government to appoint Hermann von Helmholtz, the doyen of German physics, as director.

The Institute, unlike several others constructed by individual German states in the period, was to differ from them in being an institution for all of Germany, in casting aside teaching duties for its employees, and in promoting a mixture of science and precision technology.[302] The majority of members of the Reichsanstalt board were concerned with 'practical interests', and comprised chiefly experimental physicists, technologists and instrument-makers.

The PTR rapidly became the dominant German scientific institute by a combination of attracting first-rate scientists and gaining a voice in two journals. The editor of the *Annalen der Physik*, Germany's premier physics journal, agreed to publish all manuscripts from the PTR on the subject of pure physics. Similarly, the *Zeitschrift für Instrumentenkunde*, devoted to scientific technology and precision mechanics and optics, developed a close relationship with the Technical Section of the new Reichsanstalt.[303]

The early Reichsanstalt was a closely organised and hierarchical institution. Helmholtz, its first and most charismatic leader, provided a strong sense of unity, making the rounds of the young workers 'like a doctor in a clinic. . . to see how his young interns were doing'.[304] While Helmholtz surrounded himself with capable young scientists, the style of work was quite unlike a university. Each scientist at the institution was directed to undertake particular projects, unlike their academic colleagues who were more free to choose the research topics they found interesting.

The study of heat radiation was one of the first successes of the PTR. Cahan has argued persuasively that 'the practical needs of the German illumination industry – better temperature measurements and better understanding of the economy of heat

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[301]Cahan, *ibid.*, 39.

[302]D. Cahan, 'The institutional revolution in German physics, 1865-1914', *Hist. Stud. Phys. Biol. Sci.* 15 (1985), 20.

[303]Cahan, *op. cit*. [6], 83-5.

[304]*Ibid.*, 71.

and light radiation – provided the institutional justification and motivation for the Reichsanstalt's blackbody work'.[305] In 1888, for example, the Optics Laboratory of the PTR was requested by the Siemens company and the Deutscher Verein für Gas- und Wasser-fachmänner (German Association of Gas and Water Specialists) to develop photometric devices and reliable standards of luminous intensity. The German navy, too, was interested in improving the photometric design of its signalling devices.[306] From these initial utilitarian pressures, the researchers undertook a programme that led towards the understanding of the laws governing the radiation from a black body.

An early success was an improvement in visual photometers. Otto Lummer (1860-1925), head of the Optics Laboratories of the Scientific and Technical Sections, and Eugen Brodhun of the Technical Section, devised the photometer head described in Chapter 3. The new photometer was an immediate success world-wide, and within a year of its commercial introduction was widely acclaimed as the best available.[307] Brodhun, a former assistant and doctoral student of Helmholtz, had moved with him to the new PTR, where he was to supervise all the running tests of the Optics Laboratory for the following 32 years. The routine investigations included certification of the Hefner standard lamp, testing the arc street lighting for Berlin, evaluating the relative performance of gas, kerosene, petroleum and electric lamps, and making comparisons of coloured light sources.[308] In 1903 alone, they performed more than 600 photometric tests.

A reliable source of luminous intensity proved more difficult to develop. On the basis of prior theoretical and experimental work, a blackbody source seemed most likely to provide an absolute intensity standard.[309] By 1894 the Reichsanstalt

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[305]*Ibid.,* 7, Chap. 4.

[306]*Ibid.,* 106.

[307]E.g. Palaz, *op. cit.*

[308]Cahan, *op. cit.*, 116.

[309]A blackbody source is defined as one that absorbs all incident energy and, as a consequence, emits a characteristic spectrum dependent only upon its temperature. Silvanus Thompson facetiously complained in 1915 of the

scientists reported a luminous standard based on glowing tungsten, and measured by a sensitive bolometer detector. This entirely ‘physical’ method was nevertheless rejected by German industry and the international community: while it gave a reproducible measurement, the platinum-bolometer arrangement related poorly to human vision. It was an extremely hot source, appearing whiter than the commonly used gas lamps; the standard itself related so-called ‘whole’ and ‘partial’ radiations (i.e. comparing the entire radiant emission of the source, including invisible emissions, to an optically filtered portion) which was a meaningless criterion according to proponents of visual photometry; and, the standard was far from trivial to set up and maintain. Despite the contentious practicality of the blackbody luminous standard, this linking of radiometric and photometric methods brought photometry a new prominence and respect. The tradition of quantitative measurement in radiometry now carried over to what the PTR scientists saw as its visible counterpart.

Alongside the environment of utilitarian research another PTR employee, Willy Wien, published ‘unofficial’ theoretical work on blackbody radiation. As his work fit in with the practical investigations, and promised to support a more direct definition of the unit of luminous intensity, the Optics Section, upon appeals from Wien, was instructed by the director to test the validity of Wien’s theory. Lummer and Wien stated that the results would be ‘as important for technology as for science’.[310] Work involved the experimental physicists of the Optics Section, theoreticians such as Wien and other scientists loosely associated with the PTR such as the infrared researcher Heinrich Rubens, employed at the nearby Technische Hochschule Charlottenburg, and Max Planck at the University of Berlin. This co-operative programme was substantially accomplished by the turn of the century, leading to Planck’s formula for the blackbody distribution of radiation. Thus, motivated by utilitarian concerns, light measurement became associated with quantitative radiometry and played a central role in the emergence of quantum theory.

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inadequacy of a language that required ‘white’ light to be defined in terms of a ‘black’ body. See J. W. Ryde, ‘C. C. Paterson 1879-1948’, *Obit. Not. Roy. Soc.* 6 (1949), 479-501.

[310]Cahan, *op. cit*, 147-9; quotation p. 148.

Cahan argues that the early successes in radiation research at the PTR were a consequence of its unique facilities and its willingness to undertake the necessary arduous precision measurements.[311] No less importantly,

> the Reichsanstalt and its physicists were motivated by a combination of pure scientific and utilitarian considerations. . . there existed utilitarian motives for pursuing this radiation research: such research would eventually advance the temperature-measuring needs of and contribute to the development of more energy-efficient lighting and heating sources for the German illuminating and heating industries.[312]

During its first fifteen years, the Reichsanstalt embodied an admirably close-knit collection of German academics, technologists and industrialists concerned with light measurement. By their very concentration and vastly superior resources, they imposed working methods and standards that were to be retained in Germany for decades. Its workers also had a close connection with photometry. The original promoter of the PTR, Werner Siemens, had been manufacturing photometric devices from the 1870s. His senior engineer, von Hefner Alteneck, designed what was to be adopted as the German intensity standard. Helmholtz, the first director of the PTR, was renowned for his work in physiology and physics, having written an acclaimed three-volume treatise on physiological optics. Other German scientists such as Heinrich Rubens used the superior facilities of the PTR for their own related research, and freely shared their results with academic physicists such as Max Planck. Most of these scientists and technologists were to become board members of the Reichsanstalt, thus contributing directly to its management and planning. Owing to the institution’s reputation for precision instrumentation, its close connections with German manufacturing and its direct publication organ the *Zeitschrift für Instrumentenkunde*, the photometric devices designed there received wide publicity and distribution. Indeed, the close links between industry and the institution made the selection of board members and subsequent directors awkward. The physicist Walther Nernst was rejected from the running for the directorship in 1905 owing to his investments in illumination manufacturing firms that sought Reichsanstalt certification for their

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[311]Abney, when asked to carry his results to a higher degree of precision, ‘not infrequently suggested “leaving it to the Germans” [‘Sir W. de W. Abney, K.C.B.’, *Proc. Roy. Soc.* A99 (1921), v].

[312]*Ibid.*, 156.

products.[313] This highly integrated techno-scientific culture was central to the success and promulgation of the PTR's photometric research.

The unrivalled position of the Reichsanstalt during the last decade of the nineteenth century was to slip in following years. While serving as a model for other national endeavours it failed, in photometry at least, to make a sustained international impact. Despite the relative prominence and success of 'radiant heat' studies through the nineteenth century, the subject foundered at the PTR and the other national laboratories in the first decades of the twentieth century. The workers at the Reichsanstalt ignored the implications of the new quantum physics, preferring to continue with experimental tests of radiation laws. As will be illustrated below, the German standards for intensity were not adopted by other countries, and the relatively limited studies of colour were quickly overtaken by research elsewhere. Nevertheless, at the turn of the century, with its important successes in precision measurement, theoretical explanation of blackbody radiation and direct channels for self-publicity supporting it, the Physikalisch-Technische Reichsanstalt was a model for the achievements possible by concerted co-operation of government, industry and technology. Scientists and industrialists in Britain and America were soon urging the formation of similar institutions in their own countries.

The National Physical Laboratory

At the National Physical Laboratory in Britain, a rather different regime was to take effect.[314] Work and facilities comparable to those at the PTR were not established until more than a decade later. When government support was first urged in 1891 for a laboratory to do the research that industry could not do, a committee of the British Association for the Advancement of Science was formed 'to consider the establishment of a National Physical Laboratory for the more accurate determination

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[313] *Ibid.*, 179.

[314] Edward Pyatt, *The National Physical Laboratory: a History* (Bristol, 1983), provides a sketchy overview of the institution, but almost entirely neglects the aspects treated in this thesis. The NPL annual *Reports* for the period provide details of staffing, finances, facilities and activities, both planned and accomplished.

of Physical Constants and for other *quantitative research*.[315] Oliver Lodge, an early promoter, noted that 'the further progress of physical science in the somewhat haphazard and amateur fashion in which it has been hitherto pursued in this country is becoming increasingly difficult, and that the quantitative portion especially should be undertaken in a permanent and publicly supported national physical laboratory on a large scale'.[316]

Photometry was not among the handful of studies originally proposed for the NPL. By its second year of operation, however, requests were being received from industry for the testing of glow (incandescent electric filament) lamps, and for the establishment of standards of light and photometry. According to the authors of the annual report, these were 'impossible to carry out' owing to 'incomplete equipment of the laboratory'.[317] The Executive Committee observed that as 'the inception of new work involves additional expenditures, it will be difficult for the present staff to undertake the charge of a Photometric Laboratory'. Although they anticipated that testing fees would eventually cover the expenditure, this would take time. Nevertheless, the committee recognised 'the necessity for photometric work'.

Funding was a severe problem. For its first two years, the NPL had been allocated £3,000 for equipment and fittings; this was supplemented by a further £4,000 in 1903. In contrast, the annual allocation for 1902 was £40,000 at the PTR, £20,000 for the French *Bureau Internationale des Poids et Mésures*, and £19,000 at the American National Bureau of Standards.[318]

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[315] R. Moseley, 'The origins and early years of the National Physical Laboratory: a chapter in the pre-history of British science policy', *Minerva* 16 (1978), 222-50; quotation p. 224 (my italics).

[316] R. Moseley, *Science, Government and Industrial Research: the Origins and Development of the National Physical Laboratory, 1900-75* (PhD thesis, Univ. Sussex, 1976), 41.

[317] NPL *Report* (Teddington, 1902), 5.

[318] *Ibid.*, 9. France did not form a national laboratory as did the other three countries. According to Harry Paul, the chief reasons were the reluctance of industry to make an investment in science and resistance by a significant number of purists to 'whoring for industry' [H. W. Paul, *From Knowledge to Power: the Rise of the Science Empire in France, 1860-1939* (Cambridge, 1985), 307]. See also D. Pestre, *Physique et Physiciens en France, 1918-1940* (Paris, 1984), 241-3.

The solution came through donations. William Preece, whose earlier photometric work has been mentioned, donated a ‘photometric outfit’ consisting of a German-manufactured visual photometer bench of the ‘Reichsanstalt pattern’ and a Harcourt pentane lamp; the Electric Power Storage Company donated a 150-cell battery for powering electrical standard lamps; and, the consulting engineer Alexander Trotter donated another photometer. The following year, John Fleming provided ‘three large bulb standard photometric lamps’, with others donated by the Ediswan and Incandescent Lamp companies. The Gas Engineers Institute requested the NPL to make a comparison of the intensity standards of various countries, and donated Hefner and Carcel lamps. Alexander Wright & Co. donated a flicker photometer, and £3 3s towards the NPL goal of a £2500 annual subscription.[319]

With the help of such equipment donations and a meagre budget, the Electrotechical and Optics Divisions were started in the summer of 1903 with Clifford Paterson engaged as Assistant and sole employee. Paterson undertook inter-comparisons of standard lamps with the PTR, the ‘Electrical Testing Laboratories, N.Y.’ (which the director of the NPL visited), and the NBS.[320]

Over the next five years, although the pentane burner was adopted as the NPL standard, incandescent electric lamps were receiving the most attention.[321]

By then, photometry occupied a wing of the electrotechnical building, comprising 5000 sq. ft. of floor space and including a battery room for photometry work. Four staff were devoted solely to photometry, occasionally assisted by employees engaged in other work. At least two supernumerary staff were employed as photometric

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[319]NPL *Report* (Teddington, 1904), 11. The flicker photometer had been invented by Ogden Rood in 1893 as a solution to colour photometry, following his discovery that intensity changes, but not colour differences, were perceived when samples were rapidly interchanged.

[320]*Ibid.*, 17. The director of the NPL for its first two decades, Richard T. Glazebrook (1854-1935) had worked at the Cavendish laboratory under Maxwell and Rayleigh, becoming its assistant director in 1891. As director of the NPL, he supported a combination of research useful to both science and industry. See *DSB* 5, 423-4.

[321]C. C. Paterson & E. H. Raynor, ‘Photometry at the National Physical Laboratory’, *Illum. Eng.* 1 (1908), 845-54.

observers. The initial activities, dedicated almost wholly to lamp photometry, were later augmented by 'contract' work for the Home Office Committee on Factory Lighting, of which Paterson was a representative.

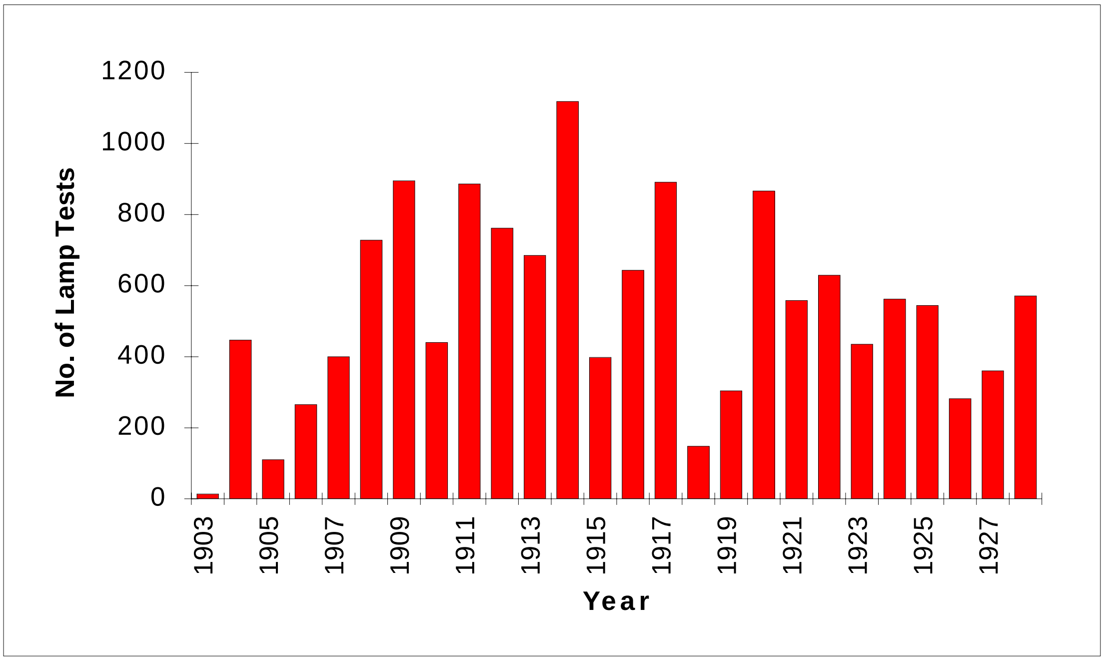

Fig. 10 Lamps tested at the NPL during its first quarter-century. *Source:* NPL Annual *Report* (1901-1924).

Paterson left the NPL after the war to become research director at the General Electric Company (GEC). Facilities and projects kept expanding at the NPL with John Walsh as Senior Assistant responsible for photometry. Within a year of Paterson's departure and the war's end, other government departments were clamouring for various photometric researches to be carried out by the NPL. By 1923 over a dozen special projects had splintered the work of the Division, diverting it from its original task of standardisation.[322] The meticulous cross-comparisons of the pentane standard with electric lamps and with the lamps of other countries which occupied nearly fifteen years' work were completed and set aside; international agreement on the use of incandescent lamp sub-standards in 1921 meant that the

[322]NPL *Report* (Teddington, 1923). The projects included work for the Commission Internationale de l'Éclairage, photometric studies of thermionic tube ageing for the Radio Research Board, ships' navigation lamps for the Board of Trade, motor car headlamps for the Ministry of Transport, miners' lamps for the Home Office, and the lighting of the National Portrait Gallery and the House of Commons.

pentane lamp was retained only for occasional national usage. Illumination and lighting studies now assumed great importance for the Division. A special 'illumination building' was erected in 1922.[323] Later, an additional 600 sq. ft. of space was found in an old house on the laboratory grounds, and later still, 3000 sq. ft. borrowed from the new high voltage research building. In 1936, the facilities in the four buildings were rehoused in a large new building which incorporated a 'physical photometry' room (for light bulb tests using photoelectric measurement), a spectrophotometry and illumination research room based on visual measurements, and a photometry room for the calibration of sub-standards.[324] To John Walsh, photometry was a branch of 'technical physics' to be pursued simultaneously on theoretical, experimental and practical grounds.[325]

The growing organisation at the NPL was not universal; a strange duality of purpose operated there through the 1920s. Unlike the PTR, where photometric measurements were the domain of the well-equipped Optics Section, photometric work at the NPL straddled two departments for its first few years. It was classified as Optics in 1904 and again as Electrotechnics in 1905. The Optics Division, started when Clifford Paterson joined in 1903 but taken over by another Assistant two years later, was evolving towards specialisation in optical design and testing by the war. Paterson's Electrotechnic Photometry Division concentrated on intensity standards. Unlike its German counterpart, the NPL Optics Division had little expertise and no mandate to engage in either radiometric or photometric research. By the early 1920s, however, both NPL Divisions were becoming involved with colour research.[326]

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[323]The illumination building was used for research conducted for the Illuminating Committee of the Department of Scientific and Industrial Research, of which both Paterson and Walsh were members. The DSIR, founded in 1915, formed the Illuminating Committee in 1923. For its early years, see I. Varcoe, 'Scientists, government and organised research: the early history of the DSIR, 1914-16', *Minerva* 8 (1970), 192-217, and I. Varcoe, *Organising for Science in Britain: A Case Study* (Oxford, 1974).

[324]J. W. T. Walsh, 'Photometry at the National Physical Laboratory', *Trans. Illum. Eng. Soc.* 1 (1936), 148-54.

[325]J. W. T. Walsh, *Photometry* (London, 1929), vii.

[326]Colour research is discussed at greater length below.

Special projects in the Photometry Division required the testing of railway signal lamps, as well as measuring dissimilarly coloured light sources. On the other hand, the Optics Division had been donated a Koenig-Martins spectrophotometer, and an ‘incomplete Hilger spectrophotometer developed during the war’. As early as 1911, in fact, the Optics division had been designing visual spectrophotometers, although no object for, or results from this work were mentioned.[327] With these instruments available but unused, the Optics Division thus stated its intention to begin colorimetry research in 1922.[328] The NPL annual *Record* documents completely independent but similar research by these two groups, with no cross-references or mentions of collaboration, throughout the decade. The overlap of work was considerable: in 1924, the Photometry Division began work on colour filters that had been undertaken by the Optics Division two years earlier; in the same year, the Optics Division did preliminary research on photometers for heterochromatic photometry already completed by their counterparts in Photometry.[329] The measurement techniques of the two groups were similar, both relying exclusively on visual observation. In 1924, the redundancy of effort took a new turn when the Divisions undertook preliminary studies on the use of photoelectric cells in photometric research.[330]

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[327]NPL *Report* (Teddington, 1911). The instruments were likely intended for measuring the transmissive properties of optical glass.

[328]NPL *Report* (Teddington, 1921).

[329]NPL *Report* (Teddington, 1924), 77. Colour standardisation work was carried out by the Optics Division for the Physics Co-ordinating Research Board; the work of the Photometry Division was motivated by employees’ responsibilities as delegates to the Commission Internationale de l’Éclairage and as collaborators with the National Bureau of Standards in Washington.

[330]The *NPL Report for the Year 1924* noted that photoelectric photometers had been in use in stellar photometry for a number of years, but that gas-filled tubes had been unreliable. The Photometry Section had, in fact, been characterising selenium devices for industrial use since 1921, but these were generally employed as mere *sensors* rather than as quantitative detectors. See Chapter 6 for further discussion.

The National Bureau of Standards

Photometric work the National Bureau of Standards fell somewhere between the well-organised early PTR and the under-funded, but continually expanding, NPL. In general, its organisation closely mirrored that of its British counterpart. More than the other two institutions, however, and because of its direct administration as a government department, the NBS was efficient in proposing and imposing industrial standards.

The Bureau of Standards was founded by an act of Congress in 1901.[331] The Photometry Division of the NBS was started in the autumn of the following year with a single lab assistant in a basement room of the Coast and Geodetic Survey in Washington, D. C.; the entire Bureau of Standards had only 14 personnel in its first year. By 1908, the Bureau could claim 110 employees and the Photometry Division five, three of whom were physicists. Their work was divided into the testing of lamps (both for commercial and Bureau use) and 'investigation'.[332] The investigation was restricted to the evaluation of potential lamp standards for the first few years.[333] The first head of the photometry section was Frank A. Wolff, Jr., formerly of the office of Weights and Measures. Wolff, who had several acquaintances in Congress, had been instrumental in promoting the bill for the founding of the NBS. The Bureau itself was modelled on the Reichsanstalt, and its methods and standards initially drew heavily on its predecessor. In the initial pressure to establish laboratories of electrical and photometric references, Wolff was 'obliged, as heretofore, to send to the national

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[331]The American National Bureau of Standards at Washington, D. C., was officially entitled the Bureau of Standards for most of the period covered (1903-1933) 'through an administrative whim' [R. C. Cochrane, *Measures for Progress: A History of the National Bureau of Standards* (Washington, D. C., 1966), 332]. I will, for consistency, use the abbreviation NBS in references to it.

[332]Evaluation of lamps as secondary standards continued for many years. The charges in 1916 were $3 to $5 for 'seasoning' and standardising lamps, $1 for candlepower tests, and $2 to $4 for tests of lifetime [*Circular of the Bureau of Standards 6: Fees for Electric, Magnetic and Photometric Testing* (Washington, D.C., 1916)].

[333]E. P. Hyde, 'Photometry at the United States Bureau of Standards', *Illum. Eng.* 1 (1908), 761-70.

standardising laboratories of Germany and England for verification the large class of alternating current measuring instruments, condensers, and photometric standards.[334] His work was carried out in temporary headquarters in downtown Washington for three and a half years. By October 1904, the NBS was established in a purpose-built facility on the outskirts of Washington, D.C. Photometric standards were, from the outset, part of the planned activities. Photometric laboratories occupied one floor of the mechanical engineering building, and half an attic. The other, much larger, building housed the Physical laboratory, which was to include a photometric standards laboratory. This was, however, forced to give way to a lunch room, which had been omitted from the architectural design.[335] Upon completion of the new facilities, Wolff's work was turned over to Edward P. Hyde from Johns Hopkins University in Maryland. The entire staff of the NBS comprised 58 persons at the opening of the new facility.[336]

The American government soon made use of the NBS to ensure the quality of the products it purchased. The work of the photometry section was instrumental in persuading the government to move towards increasing industrial regulation. Incandescent lamps for Federal offices were, by 1904, being purchased at the rate of one million per year. When the purchasing agency sent a sample of light bulbs to the Bureau for tests for the first time that year, three quarters were rejected because they failed the manufacturers' own specifications for luminosity. This success of the Bureau in weeding out unsatisfactory electric lamps was noted at Government hearings on weights and measures, the incident leading to a wave of reform through the Government service to set specifications and tests for items as varied as clinical thermometers, chemical glassware and mucilages.[337] In 1907, representatives of incandescent lamp manufacturers met with NBS engineers to adopt standard specifications. These detailed the power consumption required to produce a given illumination, and the minimum acceptable 'lifetime', defined as the time required to

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[334]Coast and Geodetic Survey, *Annual Report,* quoted in Cochrane, *op. cit.*, 58.

[335]Cochrane, *op. cit.*, 71-2.

[336]The NPL, too, had a staff of 58 in 1904, two of whom were assigned to photometry.

[337]Cochrane, *op. cit.*, p. 90-1.

drop to 80% of their original light output. Ninety per cent of a test lot of bulbs was required to pass the specifications or the entire lot would be rejected.[338] The circular published by the Bureau called attention to the low illuminating efficiency of carbon filament lamps compared to the newer metal filament types. Avoiding outright mention of the brand name, another circular nevertheless made clear the marketing practices of the manufacturer: ‘The tungsten lamp has been improved in quality and reduced in price to such an extent that no customer can afford to use carbon lamps, even if he were paid a bonus on each lamp for so doing. Many householders cling to the use of carbon lamps because they are usually supplied free’.[339] Such lamps required nearly three times more power than the Mazda tungsten lamp, a commonly available alternative.[340]

The photometry of gas lamps similarly led the Bureau towards standards setting and regulation. In 1905, the Bureau of Corporations requested the NBS to investigate the illuminating power of commercial kerosene oils. When forty such oils were tested the following year, the staff of the Photometry section concluded that even the Hefner amyl acetate and Harcourt pentane standard lamps were inadequately stable. Citing the results of this preliminary work, the Bureau requested from Congress a special $10,000 appropriation for a two-year study of gas and oil illuminants in 1908. This was to be the first such specially funded investigation of the Bureau, a practice that was repeated almost yearly until 1936, when Congress began to lump special NBS research projects into general funds. The early special appropriations, being individually requested and granted by Congress, thus had a relatively high profile and gained both government and public attention.

As at the NPL, the early photometric work had an uncertain home. Photometry was decidedly *not* a branch of Optics, however. A graduate chemist from the University of Wisconsin was hired and sent for courses in gas engineering, and

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[338]NBS Circular 13, *Standard Specifications for Incandescent Electric Lamps* (Washington, D.C., 1907).

[339]NBS Circular 55, *Measurements for the Household* (Washington, 1915).

[340]General Electric, successor to the Edison company, owned the majority of manufacturing patents on incandescent lamps in America, which it licensed to at least 33 other companies.

then put in charge of the gas photometry investigation as a member of the Electrical Division. The work of his group over the next two years led to standards for illuminating and heating gas. In its circular on the subject, the NBS recommended that gas supplies be priced by their heating and illuminating power rather than by volume, as was the current practice in most cities.[341] This 'entirely advisory' information was disputed by the gas industry for a decade before agreement was reached to sell gas on this basis. The Electrical Division of the NBS continued to be responsible for gas photometry until the early 1920s, when the work was transferred to the Chemistry Division.

During the First World War, the photometry section switched priorities to searchlights and other forms of military illumination. The staff of the photometry section expanded to seven. After the war, the photometric work at the NBS was a notable part of a general crusade for standardisation, which sought to simplify the variety and complexity of commercial products and thereby improve efficiency and competitiveness.[342] The standardisation of electric lamps, gas purity and lighting systems were highly visible early successes.

Unlike photometry, radiometry at the NBS was a subject substantially uninfluenced by commercial pressures or government directives (it had, for this reason, played a minor role at the NPL). Perhaps as a result, the growth of light measurement responsibilities was rather *ad hoc* in the early years. For example, a promising young graduate who had done his PhD work in infrared spectroscopy was hired in 1903 to head the Radiometry division. William Coblentz (1873-1962) kept this position, along with 'one or two minor assistants', for nearly 40 years.[343] In seeking practical justification for his post, Coblentz supplemented his radiometric research over the following years with work on visual response, ultraviolet filters and

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[341]NBS Circular 32, *State and Municipal Regulations for the Quality, Distribution and Testing of Illuminating Gas* (Washington, D.C., 1911), and anon., 'Circular on regulations for illuminating gas', *J. Franklin Inst.* 173 (1912), 509-10.

[342]For a description of the American 'crusade for standardisation' between the wars, see Cochrane, *op. cit.*, 253-63.

[343]W. Meggers, 'William Weber Coblentz', *Biog. Mem. Nat. Acad. Sci.* 39 (1967), 55-102.

even the radiant heat losses of pig enclosures. During the depression, Coblentz worked on standards of ultraviolet radiation. Hospitals and several industries had sought means to calibrate the photoelectric dosage intensity meters used for measuring UV radiation. Around 1931, ultraviolet lamps became commercially available as ‘household health aids’. The NBS produced a standard consisting of a quartz-mercury arc lamp calibrated in absolute units in 1936.[344] Unlike the PTR, which had sought to merge radiometry and photometry, the NBS enforced a distinction between radiometric and photometric work. Colorimetry and radiometry were subsections of the Optics Division, while photometry and illuminating engineering were in the scope of the Electricity Division.[345] Coblentz, responsible for radiometric studies principally in the infrared and later in the ultraviolet – bracketing the visible spectrum – was warned by his superiors to leave visible-light photometry to the Photometry Division.[346]

As at the NPL, the work of the Electrotechnical photometry and Optics divisions began to overlap after the First World War. Both began investigations into colour measurement and standardisation. The Photometry Division was motivated by extensions of ‘white-light’ photometry to lights of different tints. The Optics division, on the other hand, felt that the design and evaluation of optical filters for signalling lamps fell naturally into its domain.

Colour at the national laboratories

The measurement of colour was a subject distinct from photometry in the early national laboratories, but one increasingly merged with it in terms of technique and measurement objectives.

By 1914, there was an increasing interest in and demand from industry for a general systematisation of colour. Industrial applications of colour matching were numerous, most having been developed in isolation to suit particular industries. The

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[344]Cochrane, *op. cit.*, 338.

[345]Anon, ‘The National Bureau of Standards – its functions and activities’, *NBS circular no. 1* (Washington, 1925), p. 2.

[346]W. Meggers, *op. cit.*

American, and then the British, national laboratories began to study colorimetry as part of the work of their Optics sections. This work progressed independently of the radiometric and photometric activities of their electrotechnical laboratories, although there was occasional overlap of personnel and much commonality of technique. Interest in colorimetric research was considerably lower in Germany and France, where physical photometry retained the most attention.[347] Although there was a large body of German work following the physiological optics research of Hermann von Helmholtz and Ewald Hering from the latter part of the nineteenth century, this made little impact in England and America.[348] The American investigators, with a growing body of recent studies behind them, were quick to denigrate foreign research. In a 1925 summary of advances in colorimetry, a reviewer from the American National Bureau of Standards mentioned Wilhelm Ostwald's *Farbenlehre* as typical of current German work, describing its author as 'very far from being abreast of current knowledge and practice'.[349]

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[347]Political and social factors emphasised these technical divisions. Colorimetry drew increasing interest after WWI, when German contributions to international science were restricted. French light measurement was dominated by individuals who had already made an international mark on heterochromatic photometry and intensity standards, leads which were actively pursued both by university research. Coupled with a national self-absorption for French science, this success with physical photometry contributed to French scientists' neglect of colorimetry. For a discussion of the insularity of French physics in the inter-war period, see Pestre, *op. cit.*, especially Chap. 5.

[348]Part of the reason for this was the lack of English translations. Helmholtz's *Physiological Optics* was not translated until 1924, and Hering's *Spatial Sense and Movements of the Eye* not until 1942. For a good account of the internecine disputes between these two schools of German research, see R. Steven Turner, 'Vision studies in Germany: Helmholtz versus Hering', *Osiris* 8, 80-103 and 'Paradigms and productivity: the case of physiological optics, 1840-94', *Soc. Stud. Sci.* 17 (1987), 35-68. For an earlier, positivistic history of colour science, see P. J. Bouma, *Physical Aspects of Colour* (Eindhoven, 1944), 199-222.

[349]I. G. Priest, 'Report of the Committee on Photometry and Radiometry for 1924-25', *JOSA & RSI* 11 (1925), 357-69; quotation p. 366. Friedrich Wilhelm Ostwald (1853-1932), a Nobel-prize winning chemist, developed a colour system based on a triangle having black, white and pure colour corners. His system, first published in 1917, became widely known and was the basis of the Natural Colour System (NCS) later adopted in Sweden. He also wrote extensively on colour harmony through the 1920s, gaining considerable attention in the UK and America. See *DSB* 15, 455-69.

The Bureau of Standards had begun its involvement with colour measurement in 1902.[350] From the beginning, it made use of existing empirical systems. The artist Albert H. Munsell contacted the director of the Bureau soon after its formation in 1901, 'asking about color'. Munsell formed a company to market his colour charts, educational materials and books in 1917, the year before his death. Over the following decades, the Munsell Color Company under the direction of his son funded seven research associates at the NBS.[351] One of these, Irwin Priest, headed the Colorimetry section from 1913 until his death in 1932, and was influential in the fledgling Optical Society of America, becoming its president in the late twenties.[352] Priest provided considerable support in the planning and operation of the Munsell company. Another research associate at the NBS, Deane Judd (1900-1972), was a central figure in defining colour standards that were eventually adopted by the Commission Internationale de l'Éclairage. Contact with the Munsell Company was close throughout the history of the NBS. Much of this centred on putting the original empirical system on a more regular footing. For example, the investigators used spectrophotometers to measure the reflectance of the various Munsell colours as a function of wavelength, and then adjusted the colour steps to follow a more regular mathematical sequence, thus attempting to *mathematise* or idealise human colour vision. A considerable amount of collaborative work took place at the Munsell Research Laboratory in Baltimore (founded in 1922), where seven individuals were assigned to mainly scientific work. Similar work in Britain was scattered through

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[350] K. L. Kelly, ''Colorimetry and Spectrophotometry: a bibliography of NBS publications January 1906 through January 1973', *NBS Special Publication 393* (Washington, 1974).

[351] 'Research associates' were a response to inadequate funding at the NBS. In 1919, its director proposed to trade associations that 'where specific researches on important problems affecting their industry, they send qualified men to the Bureau to do this research.' These research associates would be paid by industry, and their results published and made available to all by the NBS. See Cochrane, *op. cit.*, 224-5.

[352] H. E. Ives, 'Irwin Gillespie Priest', *JOSA* 22 (1932), 503-8. Priest (1886-1932) joined the NBS in 1907 and was head of the Colorimetry Section from 1913.

separate Research Associations, which published relatively little.[353] In contrast, the result of the more open American research was forty collaborative papers before the Second World War.[354]

Rexmond Cochrane has written that 'the field of research at the Bureau in which undoubtedly the greatest variety of industries and interests had a vital concern was the standardisation of color'.[355] The NBS frequently served as the arbiter of disputes. In 1912, representatives of the butter, oleomargarine and cottonseed oil industries requested help in colour-grading their products. Other queries dealt with the colour of paints, cement, porcelain, tobacco, foods, and water purity. Irwin Priest, who had been hired in 1907 to conduct the Bureau's work in spectroscopy and applied optics, was moved to colorimetry in 1915. Investigating the use of spectrophotometric measurements for colour analysis, Priest was won over to this technique. By 1921, he was promoting colour standardisation based on a carefully defined 'white light'. Based on a physical definition of colour, his ideas aimed at rendering the observer a minor and controlled part of colour measurement.

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[353]Industrial Research Associations were promoted by the Dept. of Scientific and Industrial Research. Those concerned with photometry and colorimetry included the British Photographic Research Association (the first, set up in May, 1918), the Scientific Instrument Research Association (1918), the Electrical and Allied Industries Research Association, the Research Association for the Woollen and Worsted Industries (1918), the Glass Research Association (1919) and the Research Association of British Paint, Colour and Varnish Manufacturers (1926). Some 31 such associations had been set up by 1931. The findings of the Research Associations were considered proprietary and for the exclusive use of the member companies; the DSIR could veto their communications to foreign individuals or companies. Such commercial secrecy inhibited dissemination of knowledge in colour measurement, and placed British workers at a disadvantage compared to their American counterparts. See Moseley, *op. cit.* [25], 191; I. Varcoe, 'Co-operative Research Associations in British industry, 1918-34', *Minerva* 19 (1981), 433-63; I. Varcoe, *Organising for Science in Britain: A Case Study* (Oxford, 1974), 23; and, M. E. W. Williams, *The Precision Makers: A History of the Instruments Industry in England and France, 1870-1939* (London, 1994), 123-39.

[354]D. Nickerson, 'History of the Munsell Color System and its scientific application', *JOSA & RSI* 30 (1940), 575-86.

[355]Cochrane, *op. cit.*, 270.

Work at the NPL in England was later in starting and more limited in scope than that in America. Unlike photometry, the study of colorimetry initially had no supporters from industry. Apart from the donation of an incomplete Hilger spectrophotometer during the First World War, British industry had little connection with the NPL for colour measurement. Before the war, in fact, there were only two recorded forays into colour measurement: one in 1908 concerning the measurement of the temperature of heated bodies by optical pyrometry, carried out in the Thermometry Division of the Physics Department,[356] and the other from 1911 until the war, when a spectrophotometer was designed and built for testing the components used by the Optics Division.[357] Following the War, the Division decided that it would begin low-priority work on colour vision 'as occasion permits'.[358] The study initially involved a single observer, John Guild, who had previously been responsible for the testing of optical lenses. By 1921, however, interest grew because 'considerable attention has been devoted to it in America'.[359] The Division would do research on colour standardisation by measuring 'a representative number of colours on various types of colorimeter, both scientific and commercial'.[360] Despite a slow start and limited resources, the research now had a clearly defined programme involving the development of a standard method of measuring colour and inter-relating different commercial instruments and practices. The NPL sought a consensus in British industry by aiming at 'a general co-ordination of the various colour systems. . . and their relationships to the fundamental facts of vision with a view to the evolution of a generally acceptable scientific basis for colour specification and standardisation.[361] The first commercial system to be investigated was the thirty-year old scheme of

[356]NPL *Report* (Teddington, 1908), 20.

[357] NPL *Report* (Teddington, 1911), 64; (1912), 83; (1913), 76.

[358]NPL *Report* (Teddington, 1920), 54.

[359]NPL *Report* (Teddington, 1921), 73.

[360]*Ibid*., 71-2.

[361]NPL *Report* (Teddington, 1922), 75.

Joseph Lovibond.[362] Owing to the availability of only a single full-time investigator, progress was slow. The year 1923 was devoted to choosing a third colour between the standard green and red for railroad signal lamps, and 1924 to measurements of standard filters and instruments.[363] By 1925, however, Guild was developing a trichromatic measurement system based on standard colour filters, and collaborating with Hilger & Co. in the manufacture of a trichromatic colorimeter. With the aid of other NPL staff and observers loaned from the British Woollen and Worsted Research Association in 1927, he was able to measure the vision characteristics of seven persons, from which he refined his colour measurement system and based a set of paint colours for the British Engineering Standards Association.[364] The Guild system of colorimetry found some application in British industry. The NPL assisted the Pharmacopoeia Commission in evolving colour specifications for cod liver oil, and to the Fuel Research Station for standard colours for testing coal ash.[365] Guild's work amounted to a self-consistent body of research, but was not widely applied outside Britain.[366]

Colorimetry in Britain thus began with desultory studies at the NPL around the time of the First World War, and picked up in response to American activity. Through the Research Associations sponsored by the Department of Scientific and Industrial Research, the NPL was the locus for research and development by the mid twenties. This increasing national organisation occurred in parallel with international developments to be discussed in Chapter 7.

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[362]See Chapter 2.

[363]Similar work was being pursued independently at the NBS. See, for example, K. S. Gibson and G. K. Walker, 'Standardization and specification of railway signal colors', *JOSA* 24, (1934), 57.

[364]NPL *Report* (Teddington, 1927), 78-80; (1928), 93; (1929), 96. See also the 1931 *British Standard Schedule for Colours for Ready-Mixed Paints*, BSS 381.

[365]NPL *Report* (Teddington, 1930).

[366]Guild's researches are published in *Coll. Res. of the NPL* 20 (1928), and appeared originally in *Trans. Opt. Soc.*

Career paths

The employees of the national laboratories formed a community of practitioners distinct from their contemporaries, the illuminating engineers. Moreover, as discussed above, the photometry departments of the national laboratories were allied more closely with the electrotechnical industries than with university scientists. During the first discussions of the role of the NPL, for example, the organisers had sought to extend their support by stressing ‘engineering science and standards’ rather than ‘fundamental research’.[367] The members of the NPL departments were, nevertheless, recruited from universities. At the end of the nineteenth century, there were few permanent positions for physicists outside educational institutions.[368] The few individuals tackling industrial problems generally worked as consultants. ‘When the NPL appeared at the turn of the century, it was an oasis in the vocational desert’, writes Russell Moseley.[369] ‘The profile of new recruits was remarkably uniform’, generally men in their twenties often holding first class honours degrees and trained in physics. The NPL was organised into departments, each with a superintendent. In each department, a principal or senior assistant would be responsible for one field of activity. In accord with the NPL budget, salaries were low: in 1901, pay was about £100 per year for junior assistants, and £200-£300 for senior assistants. By the middle of the First World War, a proposal was tabled to increase salaries to £175-£235 for juniors, and £650-£750 for principal assistants. These ‘by no means lavish’ salaries were considerably lower than those available in industry.[370] In 1917, an advisory council recommended almost doubling them. Not

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[367]R. Moseley, *op. cit.* [24], 227.

[368]In 1911, only 21 British firms employed graduate physicists, rising to 40 immediately before the war. Chemists were relatively better off, but still under-employed with respect to other countries. Some 1,500 chemists, one-third with university training, were employed in British industry in 1902, contrasting with 4,000 in Germany, of whom four-fifths had university training. See I. Varcoe, ‘Scientists, government and organised research in Great Britain 1914-16: the early history of the DSIR’, *Minerva* 8 (1970), 193.

[369]R. Moseley, *op. cit.* [24], 247.

[370]E. Hutchinson, ‘Scientists and civil servants: the struggle over the National Physical Laboratory in 1918’, *Minerva* 7 (1969), 373-98. The disparity between

surprisingly, the young graduates hired easily in the first decade of the century (when career prospects for physicists were particularly low) defected to industry when opportunities arose. Few made the move, however, from the NPL into academia. A good example of this industrial-national laboratory linkage, and academic exclusion, is the career of Clifford Paterson.

Clifford Copland Paterson (1879-1948), a generation younger than the illuminating engineer Leon Gaster and nearly four decades younger than the scientific enthusiasts William Abney and J. Norman Lockyer, joined the newly founded NPL as Assistant in 1903.[371] Unlike many others at the Laboratory, he had previously been employed in technical posts in industry. Having completed sixth form specialising in engineering and physics, he spent one year in a technical college training in electrical engineering. This was followed by apprenticeships with London and Glasgow companies, and then employment as a student assistant at an electrical manufacturer for two years. On installation projects in Switzerland and Italy, he became familiar with new technology as well as with industrial relations.

One of Paterson's first projects, the investigation of the effect of atmospheric conditions on the Harcourt pentane lamp, brought him into close contact with both British industry and the members of the newly founded Illuminating Engineering Society. Indeed, the equipment donations that made his Division possible had come from William Preece and Alexander Trotter, both of whom had known William Abney, Silvanus Thompson, and Leon Gaster for over a decade. The personalities involved with British photometry, ranging from its amateur scientific aspects to illuminating engineering to government standards, thus all interacted around the turn of the century. Within a decade, though, Paterson, their junior, was a public figure and British authority on photometric standards, and the NPL was the focus of national efforts on the subject. Paterson nurtured his connections with the members of the

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salaries of scientists and administrative staff continued when responsibility for the NPL passed to the Department of Scientific and Industrial Research (DSIR). See, for example, E. Hutchinson, 'Scientists as an inferior class: the early years of the DSIR', *Minerva* 8 (1970), 396-411.

[371]Biographical details are from J. W. Ryde, 'Clifford Copland Paterson', *Obit. Not. Roy. Soc.* 6 (1949), 479-501, and R. Clayton & J. Algar, *A Scientist's War: the War Diary of Sir Clifford Paterson 1939-45*.

Illuminating Engineering Society in London and New York, and with representatives of the gas and electric lighting industries. Unlike his contemporaries, Paterson's post allowed him to develop a governmental and international perspective on the subject. As a representative of the NPL, he was an active member of the Commission Internationale de Photométrie from its second meeting in 1907, presenting papers on photometric standards in 1911. In 1913, he was appointed Secretary of the newly founded Commission Internationale de l'Éclairage, for which he had substantially drafted the statutes and constitution.[372] He remained either its Honorary Secretary or Secretary until 1948, except for a period when he served as its president (1927-31). Paterson was an active participant on governmental committees, contributing to studies of factory lighting and sitting on boards responsible for ships' lighting and signalling lamps during the First World War.[373]

Paterson was recruited after the war to become the first director of the GEC Research Laboratories, a position that he held from 1919 until his death in 1948. When he left the NPL, he took with him 'three valued members of the Laboratory Staff'.[374] The period 1916-1918 was a difficult one for the NPL, which had taken on a vast quantity of research and testing work during the war.[375] The Treasury was unwilling to fund any more posts to ease the burden on the overworked employees, or to significantly increase salaries. During the period, four senior staff members left for industrial posts.[376] When Paterson left in 1919, the funding crisis was in full swing. Paterson populated his new research facility with his subordinates from NPL. Among these were B. P. Dudding, his second-in-command; Mark Eden, from Metrology; and

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[372]The CIP and CIE are discussed further in Chapter 7.

[373]Paterson's obituary lists some two dozen offices he held. Among those related to light measurement were: chair of the Illuminating Committee of the Department of Scientific and Industrial Research; member of the Ministry of Transport Street Lighting Committee; Home Office Committee on the Lighting of Factories and Workshops. He was a founding member of the Institute of Physics in 1919, and helped establish its *Journal of Scientific Instruments* in 1922.

[374]NPL *Report* (Teddington, 1919).

[375]Discussed at greater length below.

[376]Moseley, *op. cit.* [25], 166.

Norman Campbell, the academic physicist and philosopher who had joined Paterson's department during the war. Even Paterson's secretary and carpenter made the switch, swelling the payroll to 29 people by the end of 1919. Paterson's work is discussed at greater length below.

Paterson was thus involved centrally with British photometry in the first third of the century. He was the first investigator in the subject at NPL; he attained a wide reputation by serving on governmental committees during and after the war; he was a member of the Commission Internationale de Photométrie and of its successor the Commission Internationale de l'Éclairage; sometime president of the Illuminating Engineering Society; and, he was the first director of the GEC Research Laboratories, where he oversaw considerable work on photometry and commercial photoelectric light-measurement devices.

Paterson's career contrasts with that of John William Tudor Walsh (1891-1962), his successor at the NPL. Walsh had joined Paterson's group in 1913 at the age of 22 as Junior Assistant. He was promoted to Assistant in 1916 (with only women remaining Junior Assistants), and Senior Assistant in 1921.[377] Unlike Paterson, and more typically of the now-established NPL, Walsh held an MA (Oxon.) when he was recruited by the Laboratory, and subsequently earned a doctorate.[378] He spent his entire career at the NPL, gaining status comparable to that of Paterson in the photometric community. Walsh was less active than was Paterson in government committees, and had much less involvement with industry. He attained few of the honours that Paterson had gained. On the other hand, his professional reputation in photometry arguably reached a higher point, principally due to two books on the

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[377]Walsh quickly assumed a prominent role in light measurement. He and Paterson had worked closely during the war, inventing an 'electric height finder' for which Paterson was awarded an OBE. Walsh dedicated his book *The Elementary Principles of Lighting & Photometry* (London, 1923) to Paterson 'for an invaluable training in the study and practice of photometry'.

[378]Walsh is listed in the NPL annual report as holding a PhD (London) from 1927. Probably his sole obituary is in *Trans. Illum. Eng. Soc.* 27 (1962), 214-5.

subject.[379] The dozen years between them witnessed a growing rigidity of career structure and integration within institutions.

A career regime much like that of the NPL operated at the National Bureau of Standards in Washington. There was a tendency to hire bright university graduates, often before the need for a Division had been demonstrated. One reason for the greater emphasis on recruitment of untrained university scientists rather than those with industrial experience was undoubtedly remuneration. Salaries at the new Bureau were considerably lower than in industry. In partial recompense, Stratton arranged agreements with several universities to accept research at the NBS as qualifications for advanced degrees. E. P. Hyde, the first investigator responsible for photometric research at the NBS, obtained his PhD in this way from Johns Hopkins university in 1906 for researches in photometry. With his improved academic

Table 3 Heads of the NBS photometry section 1901-1941

Section Chief	***Tenure***	***Period (years)***	***Next post***
Frank A. Wolff	1901-02	2	NBS Electrical Div.
Edward P. Hyde	1903-08	5	NELA Research Lab
Eugene C. Crittenden	1909-17	8	NBS Electrical Div.
A. Hadley Taylor	1918-20	3	NELA Research Lab
J. Franklin Meyer	1921-41	20	Retired

credentials, however, Hyde was an attractive recruit for industry. He left his position at the NBS to become director of the National Electric Lamp Association research laboratory.[380] While the NBS managed to retain a large fraction of its section heads for decades, others left to join industry (seldom academia). This tendency is illustrated

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[379]*The Elementary Principles of Lighting and Photometry* (London, 1923) and *Photometry* (London, 1926). The latter was updated as late as 1965, three years after Walsh's death. Walsh also wrote a textbook to be used for examinations of the Association of Public Lighting Engineers.

[380]Hyde left his $2000 per year job at the NBS in 1908 to do similar research at the Edison lamp laboratories for $5000 per year. See Cochrane, *op. cit.*, 98.

by the Chiefs of the Photometry Section at NBS over its first 40 years. The short tenure of most of the Chiefs suggests that they saw the job as a stepping-stone to bigger and better things.

Comparison of the national laboratories

Photometric work in all the national laboratories grew rapidly in response to utilitarian responsibilities. The growth was spurred by, and contributed to, the increasing regulation of workplace illumination. Duncan R. Wilson of the British Factory Department had surveyed industrial lighting, particularly in textile factories and printing works, between 1909 and 1911. As a result the Home Secretary in 1912 set up a Departmental Committee 'to inquire and report as to the conditions necessary for the adequate and suitable lighting (natural and artificial) of factories and workshops'. Richard Glazebrook, Director of the NPL, was chairman. A more extensive NPL survey was carried out in 1913, comprising 4000 measurements in 57 factories.[381] The Report of the Departmental (Home Office) Committee on Lighting in Factories and Workshops, issued in 1915, gave government guidelines. These guidelines had to be put into effect by engineers and verified by inspectors. Both groups required photometric standards, instruments and measurement procedures. In America, the Illuminating Engineering Society published a lighting code in 1910, which led to regulations for factory lighting in five states.[382] During the First World War, the U.S. National Defence Advisory Council Divisional Committee on Lighting issued a similar nation-wide code.[383] In Germany, the introduction of an illuminant tax law in 1909 burdened the PTR with routine photometric testing and certification of gas and electric lamps. The NPL and its counterparts in other countries made photometric standards a major part of their work.

While all three national laboratories responded to utilitarian pressures, the directions they took were different. At the PTR, requests for intensity standards were

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[381] J. W. T. Walsh, 'The early years of illuminating engineering in Great Britain', *Trans. Illum. Eng. Soc.* 16 (1951), 49-60.

[382] Illuminating Engineering societies are discussed in the next chapter.

[383] C. E. Clewell, 'Industrial Lighting', *J. Franklin Inst.* 188 (1919), 51-90.

channelled into temperature research and radiometry. This choice of technical direction can be attributed both to the time and circumstances. In the early 1890s when the industrial requests were made, most practitioners of photometry believed the future lay in the Violle standard. This proposed unit of light, based on one square centimetre of platinum heated to the melting point, was expected to promise the simplest and most fundamental of light sources.[384] Textbooks, engineers and scientists echoed this universal expectation.[385] Moreover, German investigators such as Heinrich Rubens were already engaged in research programmes to extend and measure light of increasingly long wavelength. The Reichsanstalt's embarking on the development of a primary standard and radiometry was thus the very activity that any well-equipped and confident photometric laboratory would have undertaken at the time.

A decade later, when the NPL and NBS opened their doors, faith in a platinum standard had been shaken by the experimental difficulties encountered in stabilising the temperature of molten platinum, maintaining a clean surface, and measuring the intense white light. 'Like the mercury ohm, the Violle standard has been officially adopted again and again at International Congresses by people who have never tried to construct or even use one, and who were unaware that far greater accuracy may be obtained by less academical methods', wrote the peripatetic Alexander Trotter.[386] Despite several previous abortive attempts at realising such a physical standard, it was nevertheless still the goal mouthed by the newly organised but inexperienced photometry division of the NPL.[387] In practice, the British and American laboratories found their funding inadequate for extensive scientific research, and relegated

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[384]For a technical history of the Violle standard, see P. Fleury, *Étalons Photométriques* (Paris, 1932), Chap. 4.

[385]See, for example, E. Alglave and J. Boulard, *La Lumière Électrique: son Histoire, sa Production et son Emploi* (Paris, 1882), and Palaz, *op. cit.*

[386]A. P. Trotter, *Illumination, Its Distribution and Measurement* (London, 1911), 8.

[387]Plans for 1904, 1905 and 1906 mentioned in the NPL annual reports call for investigations of a 'primary standard of molten platinum'. See, for example, NPL *Report* (Teddington, 1903), 7. When trials were finally undertaken in 1911 with the help of the thermometry division, they were shelved without publication of results.

themselves to the pressing tasks of evaluating existing flame and electric lamp sources. With little time or experience in radiometric methods, they embraced visual photometry wholeheartedly and exclusively.

National differences affected the problems studied as well. By the 1920s, the NBS was directing its activities toward low-level applied science to benefit householders and small business.[388] Partly in response to criticisms of solving industrial problems at government expense, the NBS turned more towards academic science in the following decade. The NPL researches were motivated increasingly by projects for government departments, particularly those relating to lighting engineering.[389] The PTR turned away from both these trends, declining in international importance during this period owing to an increased emphasis on routine and test work.[390]

All three laboratories nevertheless converged towards similar working practices in the inter-war years, largely owing to restricted resources and the rise of routine standards work. According to a historian of the NBS, 'because the national laboratories both here and abroad had fewer calls on them from industry, the depression years were remembered as a time of international conferences, of many inter laboratory comparisons and exchanges of data and equipment looking to new or improved international standards.'[391] All three photometric laboratories gradually lost control of their direction, approaching an unplanned existence mediated by special requests from industry, growing routine work and increasing responsibilities for legal standards.

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[388]Publications during the period included booklets on home maintenance, budgeting and efficient purchasing.

[389]For views regarding the high proportion of government lighting projects carried out at the NPL compared to the NBS, see J. W. T. Walsh, 'Illumination research at the National Physical Laboratory', *Trans. Illum. Eng. Soc. (N.Y.)* 24 (1929), 473-86.

[390]See R. Moseley, *op. cit.* [25], 256, for a discussion.

[391]Cochrane, *op. cit.*, 336. The effect of the depression on the NBS (with nearly half the staff furloughed in 1933) is described in D. Kevles, 'Physicists and the revolt against science in the 1930s', *Phys. Today* 31 (1978), 23-30.

Industrial laboratories

Research into photometry and illumination was not restricted to government laboratories, even if it was concentrated there. The founding of research laboratories, both governmental and industrial, was a distinctive feature of the early twentieth century.[392] One source puts the number of industrial research laboratories in America as 300 in 1920, and 1625 a decade later.[393] British firms also founded research labs in the inter-war period, and were conservatively estimated in the hundreds by the end of the thirties.[394]

As noted by Michael Sanderson for electrical innovation, the large industrial research laboratories 'came to replace the universities as the source of new technology, and we cannot point to any set of achievements in the universities in this field in the inter-war years remotely comparable'.[395] The most relevant example is provided by the research laboratory created in the spring of 1908 for the National Electric Lamp Association.[396] The Nela was born in 1901, the same year as the NBS.[397] The member companies of the association emphasised its role in reducing

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[392]For the expansion of industrial laboratories, particularly in America, see, for example, M. A. Dennis, 'Accounting for research: new histories of corporate laboratories and the social history of American science', *Soc. Stud. Sci.* 17, (1987) 479-518. and J. K. Smith, Jr., 'The scientific tradition in American industrial research', *Technol. & Culture* 31 (1990), 121-31.

[393]Dupree, *Science in the Federal Government*, 337, quoted in Cochrane, *op. cit.*, 218.

[394]M. Sanderson, 'Research and the firm in British industry, 1919-39', *Sci. Stud.* 2 (1972), 107-51.

[395]*Ibid.*, 135.

[396]Another significant industrial laboratory that influenced illumination engineering and photometry is the Westinghouse Electrical and Manufacturing Co. in Pittsburgh. Photometry work at other light bulb manufacturers was more restrained. For the Dutch case, see A. Heerding, *The History of N. V. Philips' Gloeilampenfabrieken* (Cambridge, 1986). Another locus, influential in colorimetry research and in training career scientists, was the Eastman Laboratories of Kodak at Rochester, set up by C. E. Kenneth Mees in 1912.

[397]The National Electric *Lamp* Association should not be confused with The National Electric *Light* Association formed in 1885. Initially an association of arc-lighting interests, by 1905 the *Light* Association represented 508 power generating

competition. These semi-autonomous divisions were also aware of the need to develop products to compete with the more efficient metal-filament lamps being produced in Germany and Austria. In an environment of competition, marketing and government regulation the Nela Research Laboratory was conceived.[398]

The first director of the Nela Research Laboratory, Edward Hyde, had begun his career as head of photometry at the NBS. He wanted to distinguish the lab as 'pure science' rather than as 'applied art'. Speaking at one of the first meetings of the Illuminating Engineering Society in New York, he observed that 'the future of this new science, and therefore the success of this new Society, will depend on the establishment of sound basic principles'. Putting behind him the ideas current in the national laboratories, Hyde believed that the future of photometry lay squarely on the shoulders of physical and *physiological* scientists: his laboratory would, he said, stress fundamental ideas before applications, with 'co-ordination of physics and physiology, the proper co-operation of the physicist, physiologist and perhaps the psychologist. . . Differentiation of science must be accompanied by a co-operation of the scientists if the great middle fields of science are to be adequately covered'.[399] The Nela Research Laboratory was not quite the co-operative industrial enterprise that it appeared. Although the National Electric Lamp Association consisted of nominally independent lamp manufacturers, in fact 60% of the stock at that time was owned by General Electric. Despite this, Hyde felt more freedom there than he had enjoyed at the NBS. 'Pure research is something of a hobby to me', he wrote to the director of

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companies and numerous individual and associate members from as far afield as Hawaii and the Yukon territory. Its stated goals were 'to advance the art and science of the production, distribution and use of electrical energy'. The organisation saw its role as primarily educational, however, and pledged not to become 'engaged in business'. It was reorganised as the Edison Electric Institute in 1933. See J. D. Wilkes, *Power and Pedagogy: The National Electric Light Association and public education, 1919-1928* (PhD thesis., Univ. Tennessee, 1973) and B. Crickmer, 'Edison Electric Institute: the first 60 years', *Elec. Perspectives* May/June, 1993, 46-66.

[398]For an economic history, see A. A. Bright, Jr., *The Electric-Lamp Industry* (N.Y., 1949), esp. Chap. VI.

[399]E. P. Hyde, 'The physical laboratory of the National Electric Lamp Association', *Illum. Eng.* 2 (1909), 758-61.

the General Electric Research Laboratory, and for a dozen years he used his industrial laboratory as a place to exercise that hobby.[400]

By its second year of operation, the Nela laboratory had seven people 'in a small one-storey and basement brick building recently occupied by the Buckeye Electric Co.'[401] The laboratory was re-housed on a green-field site in East Cleveland in 1911. Hyde wanted the facility moved away from smoke, gas fumes and disturbances – much as the NBS site had been selected some fifteen years earlier.[402] Nela Park was, during and after the First World War, to carry out work much like that at the NBS and at the more commercially oriented General Electric Research Laboratory at Schenectady.[403]

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[400]Quoted in G. Wise, *Willis R. Whitney, General Electric and the Origins of U. S. Industrial Research* (N. Y., 1985), 257.

[401]One of the member companies. Quotation from ref [108].

[402]J. A. Cox, *A Century of Light* (N. Y., 1980), 196.

[403]During the war, for example, the laboratory designed signalling lamps and investigated optical glass, flares and camouflage, as the NBS was doing. This, along with 'many projects in testing and the creation of new light-measuring instruments, kept the staffs well occupied. . . at Nela Park'. See P. W. Keating, *Lamps for a Brighter America: a history of the General Electric lamp business* (N. Y., 1954), 82, 122-3.

Fig. 11 Nela Research Laboratory, National Lamp Works of General Electric, Cleveland, Ohio, where 'only pure research relating to the physics of illumination and its physiological and psychological effects on the human organism is conducted'. *Source:* A. P. M. Fleming and J. G. Pearce, *Research in Industry* (London, 1922), 127 and 160.

Following an anti-trust suit brought against General Electric, the National Electric Lamp Association was ended in 1911.[404] The name Nela, and the research laboratory itself, remained, although now clearly identified as the National Lamp Works of General Electric. Defections from the NBS continued, too. In 1921, A. Hadley Taylor, at the time responsible for photometry and illuminating engineering at NBS, moved to the Nela Park laboratory. In the same year, Ernest Nichols succeeded Hyde. Like his predecessor, Nichols saw the laboratory as favourable to basic research:

> The position offers complete freedom in the choice of research problems, and places at my unhampered disposal such human and material resources as no university I know of can at present afford.[405]

[404]General Electric was the chief of 34 defendants in the suit, which disclosed the company's interests in the National Electric Lamp Association (by now owning 75%, with GE and NELA together producing 80% of American lamps). The court ordered that the National Electric Lamp Association be dissolved, that GE do business only in its own name, and that it refrain from the price-fixing of incandescent lamps. See J. W. Hammond, *Men and Volts: the Story of General Electric* (Philadelphia, 1941), p. 340-3, and Bright, *op. cit.* 151-9.

[405]Quoted in Wise, *op. cit.*, 257.

So unhampered were his options that Nichols renamed the facility the Pure Research Laboratory. Like Hyde, he directed its researches over a range of studies from the physics of light sources to the physiology of vision. Upon Nichols' death in 1924, though, General Electric re-evaluated the function of Nela Park and reorganised it towards more direct industrial research. Its new director, Matthew Luckiesh (b. 1883), publicised the laboratory's work in lighting research.[406] The laboratory also undertook an educational role by organising short courses on illuminating engineering, leading to its identification as 'the university of light'.[407]

The large profits at risk encouraged other electrical manufacturers to launch research laboratories. The British version of General Electric set up a major laboratory to concentrate on lighting and thermionic valves.[408] The GEC Ltd. Research Laboratory at Wembley was conceived in 1916, and first came into being early in 1919.[409] The formal opening of purpose-built facilities was in February 1923.

The company's aims were signalled by the research director it sought. Clifford Paterson's work in evaluating commercial incandescent lamps while at the NPL brought him into contact with the Osram Lamp Works, a company founded

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[406]*The Journal of the Franklin Institute* published research notes from both government and major commercial research laboratories, several of which were carrying out work in photometry. A number of individuals who were to become prominent in photometry and colorimetry in the following decade published early work in the journal, including Leonard Trolland at NELA, P. G. Nutting at Eastman Kodak, Irving Langmuir at General Electric and Harold Ives at the United Gas Improvement Company.

[407]Noble, *op. cit.*, 122-3 and 171-3.

[408]The General Electric Research Laboratory in America was much larger, but concentrated on incandescent lamp development and lighting arrangements rather than intensity measurement. The two companies had no financial connection except in the period 1928-34. See L. S. Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876-1926* (Cambridge, 1985), 104, and G. Wise, *Willis R. Whitney, General Electric, and the Origins of U.S. Industrial Research* (N. Y., 1985).

[409]R. Clayton and J. Algar, *The GEC Research Laboratories 1919-1984* (London, 1989), Chap. 1. Much of the information in this section is based on information given in a talk and privately circulated article by Paterson, *A Confidential History of the Research Laboratories* (1945) and unpublished GEC reports quoted in the book.

jointly by GEC and the German company DGA. Representatives of the company sought Paterson's suggestion of someone to organise a research department at Osram. Little came of the proposal for two years, but by the end of the war, Paterson's ideas about a research laboratory had developed and Osram had been bought outright by GEC from the Government Trustee of Enemy Property. Paterson himself took on the planning of a research laboratory for this enlarged company.

The first staff worked at a wooden building at the Osram Lamp and Valve Works at Hammersmith. Early work at the Laboratory centred on investigations of lamp design and manufacture. The first work on photometry appears to have been a proposal for a spherical integrating photometer, to be used to measure the total radiant output of lamps.[410]

By the spring of 1920, at least nine GEC units were using or requesting the use of the Research Laboratories.[411] Among these were the Osram GEC Lamp Works and the Salford Instrument Works, a small company specialising in the manufacture of electrical measuring instruments. By the time of the opening of the new laboratory at Wembley in 1923, work was in progress in lamps, valves, and photometry. Problems of lighting continued to receive attention. Paterson had been chairman of a BSI Committee on street lighting for many years. One of the GEC scientists, J. M. Waldram, took over the chairmanship later. Paterson also served on a Departmental Committee of the Ministry of Transport, on which Waldram was the member of an Experimental Committee.[412]

Along with valves for radio broadcast, GEC researched photoelectric devices. Paterson took a direct interest in these activities, noting with satisfaction that his workers 'have probably devoted as much attention to photoelectric cells as any group

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[410]A version of this device was commercialised a decade later: see anon., 'The 19th annual exhibition of the Physical Society and the Optical Society', *Illum. Eng.* 22 (1929), 42.

[411]Clayton & Algar, *op. cit.*, p. 45.

[412]*Ibid.*, 100.

of workers in the world.'[413] Although the photoelectric research received no mention in the official GEC history,[414] it was a significant effort during the 1920s and 1930s. Norman Campbell and his co-workers publicised their work and products by publishing books on the practical usage of photoelectric tubes.[415]

Photometry and World War I

A description of the institutionalisation of light measurement would be incomplete without a discussion of the major organisational event of the early twentieth century, World War I. Unlike the Second World War, however, which profoundly altered the course of the subject, the influence of the Great War was of only indirect importance to photometry.[416]

The PTR was the most affected of the national laboratories. Fully half of the personnel joined the German armed forces in the first months of the war. The reduced staff were occupied primarily in military-related work 'of a minor, testing nature'.[417] With 22 senior scientists absent, travel curtailed and research funds withheld, little research into light measurement was able to continue.[418]

At the NPL, the hostilities were slow to affect the photometry and optics work. As late as the month before the war, representatives of the Reichsanstalt visited to

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[413]C. C. Paterson, 'Photo cells: the valves which operate by light', *J. Sci. Instr.* 9 (1932), 33-40.

[414]Clayton & Algar, *op. cit.*, 47. Mention of phototubes is limited to in-house development of instruments to evaluate fluorescent lighting.

[415]N. R. Campbell & D. Ritchie, *Photoelectric Cells: Their Properties, Use and Applications* (London, 1929), and R. C. Walker. & T. M. C. Lance, *Photoelectric Cell Applications* (London, 1933). The work of the GEC laboratory is discussed in Chapter 6.

[416]The Second World War led to an identification of physical light measurement as a subject of military importance, particularly for aircraft and missile detection and for the analysis of materials by spectrophotometry. The vision-based technology universal during WWI precluded such military interest.

[417]Cahan, *op. cit.* 225-6.

[418]In 1916, however, the PTR director awarded 2000 marks for constructing a blackbody radiator to be used as a unit of luminous intensity. See *ibid.*, 226-7.

compare standards. The war's first consequence was the increased workload caused by the quarter of NPL employees who had immediately volunteered for service. The loss of two observers and a laboratory boy burdened the remaining five Photometry staff with additional work. By late 1915, the increase in investigations for government departments prevented more staff from volunteering. Disqualified men and female temporary staff more than doubled the size of the Physics Division, although the Photometry and Optics Sections were unaffected.[419]

During the war, the activities of the Photometry Section remained evenly split between 'routine testing' and 'investigative, research and installation tasks'.[420] Among the 'several special confidential investigations' for Government departments were studies of the intensity of luminous dials for watches and instruments, and the development of a height finder for anti-aircraft guns.[421] The Optics Division reported a greatly increased workload owing to the routine testing of binoculars, theodolites and other war-related certification, and the urgent evaluation of optical glass manufacture.

The primary effect of the war at the NPL was organisational. In 1918, the newly created Department of Scientific and Industrial Research was given responsibility for the administration of the Laboratory. The DSIR funded research into building illumination after the war, an effort that demanded considerable resources. As already noted, dissatisfaction with salaries and workload caused several key employees, including Clifford Paterson, to leave in the last year of the war. His replacement, John Walsh, introduced the changes of administrative style that are inevitable in a small department. The increasing number of special projects did not slacken after the war, making the work of Walsh's Division considerably more fragmented than that of Paterson's.

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[419]The 61 Physics staff were joined by 89 temporary and volunteer workers, some 50 of whom were women.

[420]Routine testing was reported as occupying 55% in 1912, 45% in 1913-14, and 51% in 1914-15. [NPL *Report* (Teddington, 1912, 1913-14, 1914-15)].

[421]NPL *Report* (Teddington, 1915-16), 7.

The war had a comparable effect on light measurement at the NBS in Washington. Searchlight design and signalling lamps for ships demanded the resources of the Photometry Division, as they did at the NPL. Colour research, principally for camouflage design, also gained the attention of the Optics Division. In 1916, the director of the NBS requested government funding for special work on colour standards, noting that:

> There never was a time in the history of the country when we should be looking at such matters as critically as at present. The items submitted – I think I can say all of them – are as fundamentally concerned with both industrial and military preparedness as any that will come before you.[422]

For the most part, however, the war was a temporary diversion for the photometry and colorimetry work at the NPL and the NBS. No crucial military applications of the subjects were identified as being worthy of post-war research.[423]

Thus, at the PTR, the war hastened an already evident decline; post-war Germany would be unable to participate in international photometry.[424] For the victors, the chief effect of the war on these subjects was its demonstration of the benefits of organisation for technological change. The consequent move towards increasingly planned research by technical delegations, and the effect of German exclusion from international photometry, are discussed in Chapter 7.

Consolidation of practitioners

The first three decades of national laboratories thus witnessed a profound change in the social practice of photometry. The birth of national and industrial

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[422]J. W. Stratton, Congressional Hearings Feb 2, 1916, 991-2, quoted in Cochrane, *op. cit.*, 171.

[423]The wartime research was, however, popularised, for example in chapters on ‘Lighting conditions in war time’ and ‘searchlights and other appliances for the projection of light’, in: L. Gaster and J. S. Dow, *Modern Illuminants and Illuminating Engineering* (2nd ed., 1920).

[424]In 1919, the International Research Council (IRC), sponsored by the Allies, advocated policies of ostracism for German scholars which excluded their participation in international meetings until the mid 1920s. See, for example, D. J. Kevles, ‘Into two hostile camps: the reorganisation of international science after World War I’, *Isis* 62 (1971), 47-60.

laboratories around the turn of the century marked a transition from a growing band of enthusiasts (the illuminating engineers and a handful of astronomers) to institutionalised photometric researchers. The light measurement work at the national laboratories was a direct outgrowth of industrial pressure for standardisation and government-supported utilitarian research. These pressures provided the funding for a new class of scientist fitting imperfectly into either industry or academia, who wielded considerable influence on government purchasing, policy-making and international standards. These new career scientists and technologists, characteristic of the new century, were to direct the evolution of light measurement up to the Second World War.

The first quarter of the twentieth century was a period of consolidation in the practice and research of light intensity measurement through institutions. It was also a time for constructing new alliances. By pursuing new methods and uses of light measurement, the new organisations had fostered a splintering into specialties.[425] The classification and subdivision of the subject, however, was specific to each laboratory: *radiometric* at the PTR, *optical* and *electrotechnical* at the NPL, *chemistry-related* and *electrical* at the NBS, and *optical* and *physiological* at the Nela laboratory. By the 1920s, some practitioners were attempting to unite, or at least cross-fertilise, the various studies.[426] Illuminating engineers, in particular, were aware of the advantages of talking to optical experts. Leon Gaster, in large part responsible for the organisation of illuminating engineering in Britain two decades earlier, said when addressing the 1926 Optical Convention in London:

> the use of light, whether natural or artificial, almost invariably involves consideration of problems from two distinct aspects; from the physical side, i.e. in regard to the most efficient utilisation of the luminous energy available, and from the physiological side, i.e. in relation to the effect of this energy on the human eye. It may truly be said, therefore, that optics and illuminating

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[425]This was also a general consequence of the increase in non-academic careers for physicists. After WWI the existence of national and industrial laboratories promoted a schism between ‘applied’ and ‘pure’ physics. See S. R. Weart, ‘The rise of ‘prostituted’ physics’, *Nature* 262 (1976), 13-7.

[426]For example, C. Fabry, ‘The connection between astronomical and practical photometry’, *Trans. Illum. Eng. Soc. (NY)* 20 (1925), 12-16.

> engineering are kindred sciences, and that there are many fields of work where experts in both can co-operate with fruitful results.[427]

It was, in a way, a compromise: an admission that photometry could not live up to its nineteenth century ideal of being an objective visual science. Instead, it necessarily straddled physics and physiology, and was not entirely part of either study. The new institutions researching light measurement could not successfully compartmentalise the field into radiometric, photometric and colorimetric components. Even with increasingly organised research, the standardisation of light measurement proved difficult. The illuminating engineers, astronomers and institutionalised researchers remained separated by technological problems.

[427]L. Gaster, 'Illuminating engineering in relation to optics', *Proc. Opt. Convention* 2 (London, 1926), 297-304.

Chapter 6
Technology in Transition

The increasing social organisation described in the previous two chapters had the effects of promoting technological consensus and bureaucratising its development. These two parallel effects can be viewed to some extent separately, as they began to influence each other significantly only in the 1930s. The technological factors will therefore be discussed here, and the organisational changes treated in the next chapter.

The inter-war period marked a change in the direction and scope of photometry. Until then, the subject was driven not by technological changes but by cultural imperatives.[428] Engineering practice, centring on visual methods, remained little changed from the 1870s until the 1920s for the vast majority of photometric work.[429] By the Great War, however, astronomers were increasingly adopting physical methods of light measurement. Laboratory spectroscopists joined them in taking up these primarily photographic methods after the war, leading to a distinct divergence of practice between the scientific and engineering communities. Only when all practitioners began to employ photoelectric measurement techniques in the late 1920s did practice again coalesce to a single technique. This merging of method, the most characteristic technical feature of light measurement in the inter-war period, saw the 'subjectivity' of visual photometry decisively rejected for physical techniques. This gradual process, repeated in each community, involved the 'recasting' of photometry into less problematic terms. In the process, the human component of the measurement process was minimised, and the observer made ever more remote. Nevertheless, the first decade of photoelectric instrumentation highlighted once again a concern of earlier periods: how reliable and reproducible were the measurements, and how did they relate to human perception? The new

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[428]For the related case of the 'enculturation' of electrical current standards, see G. J. N. Gooday, 'The morals of metering and propriety of precision', Princeton Workshop Series, *The Values of Precision*, March 28, 1992.

[429]The hiatus in technological development is suggested by publication rates: see Appendix II.

technologies proved, in their own ways, to be as troublesome as their predecessor. This chapter discusses the contexts for the technological changes adopted by the scientific and engineering communities, and the specific problems surrounding those changes.

Perceptions of physical photometry

The transition from visual to photographic, and subsequently photoelectric, methods to be described below could be portrayed as a natural evolution, replacing the eye by an alternative providing more sensitivity and convenience – indeed, this is the conventional view propounded by technical histories.[430] However, there was a deeper motivation for the change relating to a growing scientific preference for physical methods. As other case studies have demonstrated, the adoption of new measurement technologies is seldom simple, and frequently has a significant cultural component.[431] While espousing rational arguments for a physical detector of light, its proponents weighted their views with tacit considerations. This point has been touched on in Chapter 3, and will be developed here at further length.

By the turn of the century, nearly all practitioners – despite their disparate backgrounds and professional goals – sought a physical alternative to the eye. The ostensible reasons for seeking an alternative differed for each community of practitioners. Four principal motivations can, however, be identified for the adoption of physical methods, namely perceptions of (i) objectivity, (ii) precision, (iii) speed and (iv) automation.

i) objectivity

The attraction of 'observer-independent' measurements was an important criterion for both scientists and engineers at the turn of the century. There were at least two aspects to this. First, human observations were increasingly labelled as

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[430]So-called 'technological determinism'.

[431]The case of the detection of ionising radiation has been discussed by J. Hughes, in 'Making technology count: how the Geiger counter got its click', seminar, Oxford University, 28 Oct. 1993; for radio astronomy, see J. Agar, 'Making a meal of the big dish: the construction of the Jodrell Bank Mark 1 radio telescope as a stable edifice, 1946-57', *BJHS* 27 (1994), 3-21.

unreliable; second, practitioners were placing greater emphasis on relating the perceptual property of *intensity* to the physical quantity of *energy*.[432]

'Observer-independent' methods were expected to be free from the distortions and complications of human vision, influences that were suspected even if not entirely elucidated. By removing the human contribution from the chain of processes that converted a light intensity into a number, the quantification was rendered simpler and intrinsically more trustworthy.[433] In describing his first attempts to employ a physical photometer, for example, the astronomer Joel Stebbins at the University of Illinois noted that 'there is no evidence of a large difference in scale between my results and those derived from visual observation, but in any event it is my opinion that the selenium photometer *gives more nearly the absolute scale* than can be obtained visually'.[434] He was enunciating several views implicitly accepted by astronomers: first, that they should be concerned with measuring *physical power* rather than *perceived intensity*; second, that visual perception was a good approximation for what they sought; and third, that a *physical* detector was necessarily better at attaining astronomers' *physical* objectives of measurement. Stebbins made no mention of the logical puzzles he posed: given only a visual and a selenium photometer, *how* could he judge one to give 'more nearly the absolute scale', and what, indeed, constituted an absolute scale? An implicit bias towards physical measurement and methods, without experimental justification, is thus revealed.

At the same time that physical methods separated photometry from its association with human factors, they brought it into line with other specialities in physical science where its proponents felt it more properly belonged. According to

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[432]Or more accurately, *power density*, expressed as energy per unit time per area or per solid angle.

[433]The importance of 'observation without an observing subject' as a precondition for non-subjective reasoning is discussed in Z. G. Swijtink, 'The objectification of observation: measurement and statistical methods in the nineteenth century', in: *The Probabilistic Revolution*, Vol. I. (Cambridge, MA, 1987), 261-86.

[434]J. Stebbins, 'The measurement of the light of stars with a selenium photometer, with an application to the variations of *Algol*', *Astrophys. J.* 32 (1910), 185-214; quotation p. 205-6 [emphasis added]. Stebbins' work is discussed at greater length below.

this view, the measurement of light intensity was merely a particular case of energy measurement. This appropriation and categorisation of the subject is illustrated by the work of the Dutch physicist L. S. Ornstein (1880-1941), who spent much of his career defining methods of intensity measurement using photographic and reference-lamp methods, and working out a theory of spectral line intensities. Looking back from the perspective of 1933 to his professional beginnings around 1910, his colleagues noted the general enthusiasm of investigators for physical methods:

> They made use of instruments which had been planned and mounted in previous years in the very room now used for this investigation, viz. a thermopile and a galvanometer, the readings of which were recorded photographically. The complete objectivity of this method greatly impressed our neophyte; it satisfied his innate craving for accuracy and certainty, and the mere sight of these documents in black and white, fixing the results of the experiments as it were in a mathematical curve, must have delighted him too.[435]

The quotation may say as much about the newly entrenched ideas of experimentalists in the 1930s as it does of the transition period. The *complete objectivity, accuracy* and *certainty* were, however, recurring themes for the early promoters of physical photometry. By 1930, these characteristics had been associated with physical photometry in principle, if not entirely implemented or verified, by all practitioners. The term *neophyte* also suggests that a new generation of investigators was responsible for championing quantitative methods in light measurement.

The linkage between photometry and energy measurement was made explicit by physical scientists in the first years of the twentieth century. The term 'mechanical equivalent of light' was commonly employed, in analogy with the term 'mechanical equivalent of heat'. This connection was problematic, however. To relate perceived intensity to physical energy, investigators were forced to *define* the average visual response, the light source, and the viewing conditions.[436] Investigators glossed over

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[435]Anon., *L. S. Ornstein: A Survey of his Work from 1908 to 1933* (Utrecht, 1933). See also H. G. Heijmans, 'The photometrical research of L. S. Ornstein 1920-1940', *Brit.-N. Amer. Joint Mtg. on the Hist. of Laboratories and Laboratory Science* (Toronto, 1992), Paper 30.3.

[436]The mechanical equivalent of light related the visual sensation to the energy, and was defined as the 'ratio of radiant flux to luminous flux for the frequency of maximum luminosity'. The value depended on the type of source employed, the definition of the colour response of an average human eye, and the wavelength of

this synthetic relationship in their enthusiasm to demonstrate a quantitative connection between light intensity and physical measurement.

The trend from visual to physical viewpoints overturned earlier scientific convictions. Not even the previously prevailing argument – that the intrinsically 'visual' characteristic of brightness demanded human observations – was reiterated in the general attraction of practitioners for physical measurements. The definition of photometry itself changed in the period from the turn of the century to the First World War: the centre of gravity had subtly shifted from the human eye to physical detectors. A new fashion, albeit one with convincing supporting arguments, had been adopted. The earlier physiological emphasis – the shared dogma of physical scientists such as Lummer and Brodhun as well as pragmatic engineers – was discarded in favour of a practical search for superior detectors. One of those converted was Leon Gaster, organiser of the Illuminating Engineering Society of London, who gave his support to physical methods:

> I agree. . . that physical photometers have great possibilities. Whilst realising the difficulties that have yet to be overcome in connection with the use of photoelectric cells and similar devices, I hope that ultimately it may be possible to devise a direct-reading photometer based on their use. A reliable instrument of this type would be of immense value in illuminating engineering.[437]

At the very least, he suggested, the adoption of physical methods would distance these studies from the response of the human eye.

ii) precision

For the researchers at the government standards laboratories, the *precision* of physical methods was stated as potentially their chief advantage. John Walsh, responsible for the NPL Photometry Division between the wars, secretary of the

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greatest sensitivity. It was most commonly calculated for a blackbody source by multiplying the blackbody power by the relative sensitivity of the average human eye. See, for example, C. V. Drysdale, 'Luminous efficiency and the mechanical equivalent of light', *Proc. Roy. Soc.* A80 (1907), 19-25; H. E. Ives, 'Note on the least mechanical equivalent of light', *JOSA* 9 (1924), 635-8; and J. W. T. Walsh, *Photometry* (London, 1926), 296.

[437] L. Gaster, 'Illuminating engineering in relation to optics', *Proc. Opt. Convention* 2 (London, 1926), 297-304.

International Commission on Illumination, and author of the widely used text *Photometry,* became a proponent of the new photoelectric methods:

> The search for a physical photometer is as old as photometry itself. . . In my opinion it is essential that photo-electric photometry should be developed. Visual photometry is adequate to meet most practical needs of the present day, but there is no doubt in my mind that a demand for much higher accuracy is inevitable sooner or later, and such accuracy is only attainable by physical methods. It has always to be borne in mind that increased accuracy in measurement means refinements in other directions, notably, as has been pointed out, in the design of electric lamps for use as standards. I feel sure that as soon as the need is indicated to lamp makers they will find a solution of the difficulties.[438]

While careful practitioners of visual photometry had been achieving measurement precision of 1% or better for decades, such results demanded the control of unpredictable human factors. These human factors were themselves unquantifiable. The degree of fatigue, or the 'normalness' of an observer's response to light could not be numerically related to the precision achieved. Physical methods promised a way of grounding *all* aspects of the measuring process in details that could be quantified. According to this view, the effects of variables such as exposure time, developer concentration and temperature would be numerically and individually determined. Thus the uncertainties of the photometric reading could be decomposed into their component contributions. This, in turn, could allow experimental details to be separately improved to reduce their contribution to the net uncertainty. As a plan of action to improve photometric precision and to remove it from the conceptual mire of human visual response, this physical approach was attractive to scientists.

Yet this programme was based on faith rather than demonstrated potential. As discussed below, the NPL through the 1920s struggled to develop physical detectors that could equal the precision of visual photometry. Another justification was needed.

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[438] J. W. T. Walsh, discussing N. R. Campbell and M. K. Freeth, 'Variations in tungsten filament vacuum lamps: a study in photo-electric photometry' in *Proc. Opt. Convention* 2 (London, 1926), 253-74. As related in Chap. 5, Walsh had been working with these GEC employees to develop accurate photoelectric methods of photometry since 1924. The term *accuracy* (agreement with 'reality') was less fitting than *precision* (variation from one measurement to the next) because physical methods had no obvious advantage for the former.

iii) speed

Where the astronomers made do with slow and technically difficult photographic methods, the engineers demanded speed and ease of use. Drawing an analogy with the popular Kodak cameras, one editor wrote in 1906:

> The apparatus which we describe this week also reduces photometry to the pressing of a button, while the selenium "does the rest" and it can be used by unskilled observers.[439]

The urgency for rapid and convenient photometry rose as applications grew. At the Optical Laboratory of the Physikalisch-Technische Reichsanstalt in 1913, for example, scientists were encumbered with seven hundred photometric tests of lamps, requiring a significant fraction of their time.[440] A de-skilling of measurement would also promote mass production of standardised products such as light bulbs. A simplification was called for.

iv) automation

Closely allied to a desire for speed was a wish for the automation of photometric measurements, part of a general trend towards automatic control in engineering and industry.[441] The meaningful employment of light intensity measurements frequently led to the need to acquire large bodies of data, whether of lamp characteristics as a function of angle, paint formulations versus wavelength or photographic emulsion transparency versus position. Even rapid measurements could require tedious work by patient instrument-minders. Following World War I, such routine jobs were less attractive than formerly.[442]

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[439]Anon., editorial, *Electrician* 56 (1906), 1037.

[440]D. Cahan, *An Institute for an Empire: the Physikalisch-Technische Reichsanstalt 1871-1918* (Cambridge, 1989), 214.

[441]Stuart Bennett has written extensively on the history of automatic control. For an analysis of the attractions of automation, see '"The industrial instrument – master of industry, servant of management": automatic control in the process industries 1900-1940', *Technol.& Culture* 32 (1991), 69-81. For technical histories, see *A History of Control Engineering 1800-1930* (London, 1979) and *A History of Control Engineering 1930-1955* (London, 1993).

[442]J. Stevenson, *British Society 1914-1945* (London, 1984), 182-202.

An early proponent of automated light measurement was the MIT physicist Arthur Hardy. He developed in 1922 the first recording photoelectric spectrophotometer to study the problems of colour printing, chiefly to acquire large amounts of data quickly:

> it seemed probable that a great mass of spectrophotometric data would be required. . . The only escape from this situation seemed to lie in the direction of developing a more rapid method of spectrophotometry. There was little hope of decreasing the time required for a spectrophotometric analysis with instruments of the visual type. This type of instrument requires that the reflectance of the test sample be determined with high precision under illumination by homogeneous light of some thirty different wave-lengths within the visible region of the spectrum. Since at least five settings are usually necessary at each wave-length, the possibility that an instrument could be devised to determine these data and record them automatically seemed worthy of investigation.[443]

Hardy and others devoted as much effort to automating their measurements as to improving their precision. Their labour provided an immediate pay-off: during its first year of operation, the spectrophotometer recorded over 1000 spectra, providing a wealth of information for colour scientists. Hardy's device was widely adapted, and proved highly popular when commercialised some years later.

Automation symbolically removed the problematic observer from the measurement, making it an attractive and highly visible benefit of physical methods. By relegating the operator to interpreting graphs or numerical lists – an activity seemingly free of physiological and psychological factors – automated instruments appeared to redraw the boundaries to position photometry firmly within the realms of physical science. That such a demarcation entailed the adoption of new light detectors having their own complexities, and requiring a definition of how the visual sensation related to their replacements, was not initially an issue.

For different groups of practitioners, then, physical photometry promised distinct advantages: better objectivity, precision or speed than the eye could provide, and even the potential for removing the observer altogether. Along with these practical advantages, however, physical photometry required a change of philosophy.

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[443] A. C. Hardy, 'History of the design of the recording spectrophotometer', *JOSA* 28 (1938), 360-4.

The new physical scientists who took it up saw photometry not as a common-sense procedure intimately tied to human vision, but as a branch of energy measurement. By interpreting light measurement in this way, they reclassified the eye as one of the more unreliable detectors of radiant energy, rather than as the central element in a perception-oriented technique. This tailoring of photometry to the conceptions of physical scientists was to make it the dominant view for the first three decades of the century. The remainder of this chapter discusses how the technological transition occurred in the various technical communities.

The development of visual photometry

Routine uses of photometry such as lamp standardisation and testing had become commonplace after 1900. As a result, visual photometry became highly systematised in the first two decades of the century, serving as the sole method employed at the national and industrial laboratories involved with photometry.[444] This is not to say that these laboratories shunned physical techniques; rather, they saw their task as one of determining the brightness *as perceived by the human eye*. Bemoaning the difficulties, two engineers wrote in 1894:

> That we do have graduated slide scales in photometry means very little, for what we really want is a quantitative measure of the intensity of brain effect. And how can we do this with the brain itself? We are beset with physiological or, rather psychological, effects, and as yet there is no psychological unit which we can represent by anything concrete to give to the Board of Trade.[445]

The only option was to employ human observers. But the eye was not a detector of convenience; it was an intrinsic and central part of the apparatus. As Alexander Trotter observed, a photometer should merely furnish ‘a development of our powers’, and:

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[444]Until the early 1920s, when photoelectric techniques were investigated; see below. Commercially available photometer designs were essentially static between 1860 and 1900 in response to gas industry requirements. Compare, for example, illustrations in W. J. Dibdin, *Practical Photometry* (London, 1889) and J. Abady, *Gas Analyst’s Manual* (London, 1902).

[445]J. M. Barr & C. E. Phillips, ‘The brightness of light: its nature and measurement’, *Electrician* 32 (1894), 524-7; quotation p. 525.

> whatever results we obtain, however ingenious the apparatus used to arrive at them, and whatever the conditions we prescribe for carrying out the work, our measurements are of no value if they disagree with the common-sense estimate which anybody may make merely by using his eyes.[446]

This central role of the eye in photometry was accepted by physicists as much as by pragmatic engineers. The PTR physicists Lummer and Brodhun, inventors of the most popular visual photometer, noted:

> The purpose of practical photometry is to compare the total intensities of light sources as they are perceived by our eyes. In such a measurement of the purely *physiological* effect of flames only the eye can therefore be used; all other measuring instruments, such as the radiometer, selenium cell, bolometer and many more of the kind, are to be discarded in so far as these indicate *physical* effects of light sources.[447]

And Leon Gaster, representing illuminating engineers, echoed the physicists, observing that 'all such "physical" apparatus, besides being inconvenient in practice, is open to the objection that it does not "see" the energy impinging upon it in the same way as the eye'.[448]

Even though the intrinsic reliability of human observers was clearly poor, the laboratories sought to improve their results by carefully standardising the conditions of observation and automating the observation process. In effect, the practitioners attempted to neutralise or compensate for the variable human aspects, making them as physically based as possible by restricting measurement to highly controlled circumstances. If the observer was to be a mandatory component of the apparatus, they reasoned, then the observer would be rendered as reliable as the rails, cranks and standard lamps that shared the room.

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[446]A. P. Trotter, *Illumination: Its Distribution and Measurement* (London, 1911), 66-7.

[447]E. Lummer & E. Brodhun, 'Photometrische Untersuchungen', *Z. Instr.* 9 (1899), 41-50 and 461-5, quoted in Hans Kangro, *Early History of Planck's Radiation Law* (London, 1976), 152. The photosensitivity of selenium had been discovered by Willoughby Smith in 1872. Samuel Langley invented the *bolometer* in 1880, a detector consisting of a thin metal strip that changed resistance with temperature. The quantitative use of these electrical devices was made more practical by the development in 1882 of the D'Arsonval galvanometer.

[448]L. Gaster & J. S. Dow, *Modern Illuminants and Illuminating Engineering* (London, 2nd ed., 1920).

The strategy of standardising viewing conditions yielded immediate gains. Investigators had found that results obtained using photometers employing differently sized illuminated areas gave incompatible results.[449] Another standardisation was to restrict the range of illumination used, so that the Purkynje effect, an apparent colour change of weakly illuminated objects, was avoided.[450] By identifying ‘perturbing effects’ which caused deviations from the desired ‘linearity’ and by limiting the scope of measurements, quantification was thus made to appear increasingly plausible and, indeed, natural.

Besides controlling such instrumental and visual contributions to the measurement, serious practitioners reduced the variability of single observers by making multiple repetitions of measurements. Repeating a measurement hundreds or even thousands of times was not uncommon in precise work, and could yield repeatability of between 0.1% and 1%. If the starting conditions were suitably randomised (e.g. by beginning with the reference lamp at an arbitrary intensity with respect to the sample), multiple measurements could lower the uncertainty caused by observational factors such as fatigue or inexperience.[451]

When differently coloured lights were to be compared, even this care was not enough. Because of the differences in the colour responses of different observers, no amount of repetition or control of viewing conditions could remove the inherent personal bias. For this reason, the comparison of the pentane standard with a carbon filament electric lamp (which had relatively yellow and white tints, respectively) at the NPL necessitated the drafting of all available technical staff as observers to obtain an unbiased mean.[452] Another approach to comparing light sources of different temperature (and hence colour) was the so-called ‘cascade’ method. To compare

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[449]By the turn of the century, photometer heads were frequently designed with a field of view of 2°, causing only the fovea near the centre of the eye to be employed.

[450]‘The Purkynje effect renders the photometric comparison of differently coloured lights at low intensities almost impossible’ [J. Walsh, *Photometry* (London, 1926)].

[451]See *ibid.*, 175-80, for an account of the nature and control of personal errors in photometry.

[452]NPL *Report* (Teddington, 1911), 39.

carbon-filament lamps with the newer (and whiter) metal-filament lamps when they became commercially available, a number of intermediate sub-standards were manufactured, designed to exhibit little or no colour difference compared to the sub-standards immediately adjacent.[453] The great advantage of the cascade method was that it required few observers, even if the colour sensitivity of their eyes was distinctly different from that of the average human eye.

Such systematisation of observation could make an onerous task practicable. By 1908, Leon Gaster could wax optimistic:

> At one time, when such investigations had not yet been undertaken, the cumulative effect of unrecognised errors. . . was not infrequently ascribed to personal error; thus it came about that photometry came to be regarded as a hopelessly unreliable process, to the arbitration of which commercial matters could never be subjected. Now, however, the old sources of uncertainty are being one by one recognised and removed, and it must be recognised that photometry, well within the limits of accuracy imposed by commercial consideration, is possible.[454]

The other early twentieth-century developments in visual photometry related to efficiency and simplification to suit the routine, high-volume measurements required by industry. The speed of observations could be remarkable. The process was made as routine as possible using human workers:

> In certain lamp factories, electric glow-lamps are tested by piece-work. This is generally carried out by girls working in teams of two, one seated in front of the photometer, adjusting it, making the observations, and reading the result either in candle-power at constant pressure [i.e. voltage], or in volts for a given candle-power; the other changes the lamps and marks them.

'With freely moving equipment a measurement can be made to an accuracy of 2 or 3 per cent in 5 or 6 seconds', continued Alexander Trotter.[455] Trotter gave much consideration to measurement errors, nearly all of which were related to human

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[453]At the NPL, a series of five such lamps was used. The observer used the standard techniques of visual photometry to compare each pair of lamps in the series. The difference between the two extreme lamps was the product of the ratios of the measurements on pairs. The measurement uncertainty was, however, also increased in this technique, thus limiting the precision attainable.

[454]L. Gaster, *Illum. Eng.* 1 (1908), 794.

[455]Trotter, *op. cit.*, 192.

variations, citing ill-health, general fatigue and various forms of ocular fatigue as fatal to accurate measurement.[456]

The standardisation of visual photometry arguably reached its zenith in the establishment of legal specifications for visual instruments. An NPL staff member wrote in 1924 ‘the development of a cheap and accurate portable photometer is one of the problems of the moment. It is desirable that some standard of performance be specified for such instruments. A neutral glass is essential with most photometers of this description but many in use are far from being neutral’.[457] By the next year, the British Engineering Standards Association (BESA) had satisfied his wish, publishing a *British Standards Specification for Portable Photometers*.[458] This was followed four years later by another specification for integrating photometers, which defined attributes such as the surface reflectance, size of the reflecting sphere and diameter of viewing apertures.[459]

The adoption of standardising methodologies thus improved repeatability and went far towards legitimating the subject. But the regularisation of the human factors in visual photometry illustrates the tantalisingly unattainable goal of the reliable measurement of a ‘typical’ human perception. An alternative approach, adopted increasingly by those scientists free of the pressures of utilitarian application, was to replace the complications of the human eye with the more easily characterised vagaries of physical detectors of light. The best alternative at the turn of the century was the photographic plate.

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[456] *Ibid.*, Chap. 9.

[457] H. Buckley, ‘The field for international agreement and standardisation in illumination’, *Compte Rendu CIE* (1924), 412. From 1918, Buckley shared with John Walsh nearly all the photometric work of the Electrotechnic Division.

[458] K. Edgcumbe, ‘The British Standards specification for portable photometers (No. 230/25)’, *Illum. Eng.* 19 (1926), 70-1.

[459] K. Edgcumbe, ‘A standard specification for photometric integrators’, *Illum. Eng.* 22 (1929), 106. The BESA specification was No. 354, 1929. The integrating photometer measures the average intensity of a light source by receiving the light reflected from the interior of a diffuse white sphere or cube.

The replacement of visual by photographic methods

Despite the prevailing view that visual observation was essential for a meaningful definition of photometry, some physical scientists were willing to consider physical alternatives. William Abney, for example, interested in both vision and photography, predicted in 1893 that ‘note-book records of photometric work would soon become obsolete, and that photographic records would become general’.[460]

By the turn of the century, despite evolutionary improvements in visual photometers, *photographic* photometry began to make inroads among scientists. Part of the reason for this was analytical convenience. A photograph could record an intensity for later examination and matching by eye. This was particularly useful in astronomy, where a photographic record could be examined at convenience by one or more observers, rather than making a visual photometric reading by a single fatigued individual at the eyepiece of a telescope.[461] The ability to evaluate photographic records in an optimal setting was important to the acceptance of photographic photometry. So, too, was its ability to record the raw data. Visual photometry had no means of making a record of observations or to serve as an illustration for a publication. Photometric results had thus remained peculiarly individualised. The ability to record observations rendered the technique public.[462]

To its first users, the conceptual difficulties of photographic photometry appeared minimal. Initially, at least, photographic methods of photometry simply

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[460]Anon., ‘Capt. Abney on photometry’, *Electrician* 32 (1894), 625.

[461]The application of photographic methods to astronomy was by no means straightforward, however. Some astronomers initially suspected that photographic recording of observations, while convenient for the ‘automation’ of observations, omitted detail evident to visual observers. Moreover, its use for quantitative measurements such as the transit of Venus was criticised for possible instability of the photographic emulsion, and for a dependence of the image size on exposure conditions. See, for example, H. Rothermel, ‘Images of the sun: Warren De la Rue, George Biddell Airy and celestial photography’, *BJHS* 26 (1993), 137-69.

[462]The ability to publically witness experiments had been identified as a feature of good science since the 17th century. Photometry was thus marginalised by its requirement for closetted, individual observations.

replaced the eye by a photosensitive plate, the analysis of the resulting plates being carried out using the methods of visual observation.[463] The photographic record acted merely as an intermediary step translating the visual evaluation to a more convenient location and time. In a direct application of the visual methods of observation described in Chapter 2, practitioners either noted the point of minimum exposure on a plate (extremum detection), noted the lack of exposure (thresholding) or equated the greyness of exposed plates (matching).

The cultural context was important in determining users' perceptions of photography. Photographic methods were taken up first by the community of astronomers and then by astrophysicists for determining stellar temperatures and for classification;[464] by the first decade of the twentieth century, visual observations for stellar photometry had been completely superseded. For these astronomers, photographic photometry had unique advantages. For spectrophotometry in particular, visual methods proved simply too insensitive and time-consuming at the telescope. The photographic plate was clearly superior in this respect, being able to gradually build up an image over seconds or minutes to achieve a sensitivity far superior to that of the eye. In addition, fluctuations in brightness caused by atmospheric turbulence were averaged out by this integration process. Photographic recording also improved upon the measurement of the intensity of stars of different colour. The visual judgement of colour intensity in spectrophotometry was a process fraught with error. Photography, in contrast, yielded a monochromatic plate from which the density could be more straightforwardly judged by eye. The problem of colour sensitivity was transferred to the photographic emulsion, which could be rendered less variable than different human observers.

From the astrophysics community, photographic photometry spread to laboratory spectroscopists, who again found that the ability of the photographic plate

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[463]Thus, for example, a photographic plate replaced the screen of the visual photometer, and recorded two adjacent patches of light. The plate would be exposed to yield two blackened areas, the optical densities of which were assumed to be proportional to the original light intensities.

[464]E.g. A. E. Wilson, 'A new photographic photometer for determining star magnitudes', *Astron. & Astrophys.* 11 (1892), 307-9.

to record a faint spectral image made it practicable where the human eye was not.[465] Again, the photographic plate averaged the irregular intensities produced by the flame or arc sources that were used for vaporising materials in spectral analysis. Photographic photometry had advantages over direct visual observation in two further circumstances, both related to spectrophotometry. First, when measuring the relative brightness of different portions of a spectrum when the light source is fluctuating, a method of simultaneously recording all wavelengths is required. Second, when observing the short ultraviolet wavelengths to which the eye is insensitive or blind, photography was unavoidable.

Applied to scientific measurement in the last decades of the nineteenth century, photography became the principal photometric method for scientists by 1920 and found its widest routine application in spectroscopic research. The complexities of the technology were well understood, and its methods rendered routine, by the mid 1920s.[466] This new technology remodelled photometry to emphasise features important to the astronomical community: instead of obtaining measurements linked to human perception, the practitioners stressed the ability to integrate weak images and to analyse records.

Despite astronomers' unproblematic exploitation of the seemingly straightforward analogy between visual and photographic methods of photometry, photographic photometry made no inroads whatsoever into industrial applications. Indeed, the use of photographic in preference to visual methods serves as a reasonable criterion for dividing engineering and scientific uses.

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[465]The route for this technological exchange was undoubtedly through astrophysicists, who themselves employed laboratory spectroscopy to generate comparison spectra.

[466]For surveys of the state of the art, see, for example, A. E. Conrady (ed.), *Photography as a Scientific Implement* (London, 1924); G. M. Dobson, I. O. Griffith and D. N. Harrison, *Photographic Photometry: A Study of Methods of Measuring Radiation by Photographic Means* (Oxford, 1926); G. R. Harrison, 'Instruments and methods used for measuring spectral light intensities by photography', *JOSA* 19 (1929), 267-307; and, G. R. Harrison, 'Current advances in photographic photometry', *JOSA* 24 (1934), 59-71.

From the viewpoint of the illuminating engineers and standardisers of light intensity, there were good reasons to reject photographic photometry. First, it was impracticably slow and complicated. In the context of their work, the process of exposure, processing and subsequent examination of the plates by eye was pointlessly circuitous. As long as the eye served as the final arbiter of relative intensity, the only function of the photographic plate was to record the measurement. For an activity that generally did not have the leisure for subsequent analysis, photographic photometry offered no advantage. Moreover, the photographic method required standardised photosensitive materials and processing which introduced even more sources of error into the photometric evaluation. An understanding of the extraneous factors affecting photographic emulsions was only gradually becoming clear. By World War I, then, engineers were becoming separated from scientists by technique as well as by motivations.

Physical photometry for astronomers

A handful of astronomers formed the vanguard of an as-yet unelaborated physical approach, developing stellar photometry from a visual method to a technique based upon physical measurement. This conceptual development had three technological stages: first, photographic recording of the intensity, with subsequent visual analysis; next, photographic recording of the intensity with photoelectric analysis; and, finally, direct photoelectric measurement of stellar intensity. The photographic stage of the process has been discussed above; this section will deal with the technical difficulties associated with the photo-visual and photoelectric methods.

An awkward hybrid: photographic recording and visual analysis

Photographic recording of stellar intensities originated with William Bond at the Harvard College Observatory, who in the 1850s related stellar intensities to the diameters of the images they formed on photographic plates.[467] The technique, rendered reasonably precise by his successors, relied upon calibrating the relationship between the image diameter and apparent brightness. The image formed, although

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[467] D. Norman, 'The development of astronomical photography', *Osiris* 5 (1938), 560-94.

theoretically a minute point, in practice consisted of a dark centre surrounded by a halo of radially decreasing exposure, caused by the optical limitations of the telescope. The size of the image recorded also depended on the sensitivity of the photographic plate. Like Bond before them, David Gill and J. C. Kapteyn, who used photographic methods between 1895 and 1900 for their *Cape Photometric Durchmusterung* catalogue, simply measured the photographic diameters.[468] As the successors to Bond discovered, the brightness of a star affected not only the *diameter* of a photographic image, but also its *density*. To minimise the complexity of the effect, some investigators defocused the telescope to yield a blurred spot and measured its density. The relationship between the smudgey image diameter and intensity thus differed depending on the quality of the telescope optics, the type of photographic plate used, exposure time, details of plate development and intensity range. The category of plate development alone included critical factors such as the chemicals used for development and fixation of the plate, development temperature, development time and agitation, with the precise method of agitation of the developing plate in the liquid significantly affecting the resulting density.[469] Measuring the diameter of the image had the advantage, however, that no estimate of intensity was needed. Photometry was again transmuted: the problems of photometric judgement were replaced by a mechanised process of exposure, chemical processing and metrology.[470]

The alternative to this metric technique of photometry was a more conventional visual estimation of the greyness of the exposed plate. William Abney, for example, compared the 'photographic values' of moonlight and starlight with a

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[468]R. L. Waterfield, *A Hundred Years of Astronomy* (London, 1938), 90-5, and Lundmark, *op. cit.* 299-300.

[469]G. M. Dobson, I. O. Griffith & D. N. Harrison, *Photographic Photometry* (Oxford, 1926).

[470]Some human judgement of intensity did remain, however: the stellar image generally appeared fuzzy, so that the measured diameter depended upon the gray level chosen as the true 'edge'. This uncertainty was sometimes reduced by employing 'hard' developers and plates which yielded higher contrast (and hence more sharply defined images), or by multiple copying of the plate to achieve this result. See *ibid*., 42-3.

candle.[471] Unlike simple visual observation, the photographic technique involved several steps. Abney first prepared a photographic plate having a series of stepped exposures to yield a gradation of density. He then used this plate as a neutral density filter through which his test lights shone to expose a fresh photographic plate. From the resulting exposures using moonlight and candlelight, he visually compared the grey tints of the stepped exposures to determine their difference.[472] The measurement of the greyness of point-like stellar images was difficult without microscopic examination. By either diffusing or defocusing the image, however, a larger, relatively uniform spot could be obtained which was more amenable to analysis. In some cases, observers used a combination of diameter measurement and grey-level matching for stellar photometry. The series of steps required in photographic/visual photometry are illustrated in Fig. 12.

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[471]W. Abney, 'The photographic values of moonlight and starlight compared with the light of a standard candle', *Proc. Roy. Soc.* 59 (1896), 314-25.

[472]By this technique Abney estimated that for Jupiter 'it would not be far wrong to assume that it is equivalent to a candle placed at 800 feet from the screen' and that 'moonlight is 44 times brighter than starlight when unabsorbed by more than 1 atmosphere' [*Ibid.*, 324-5].

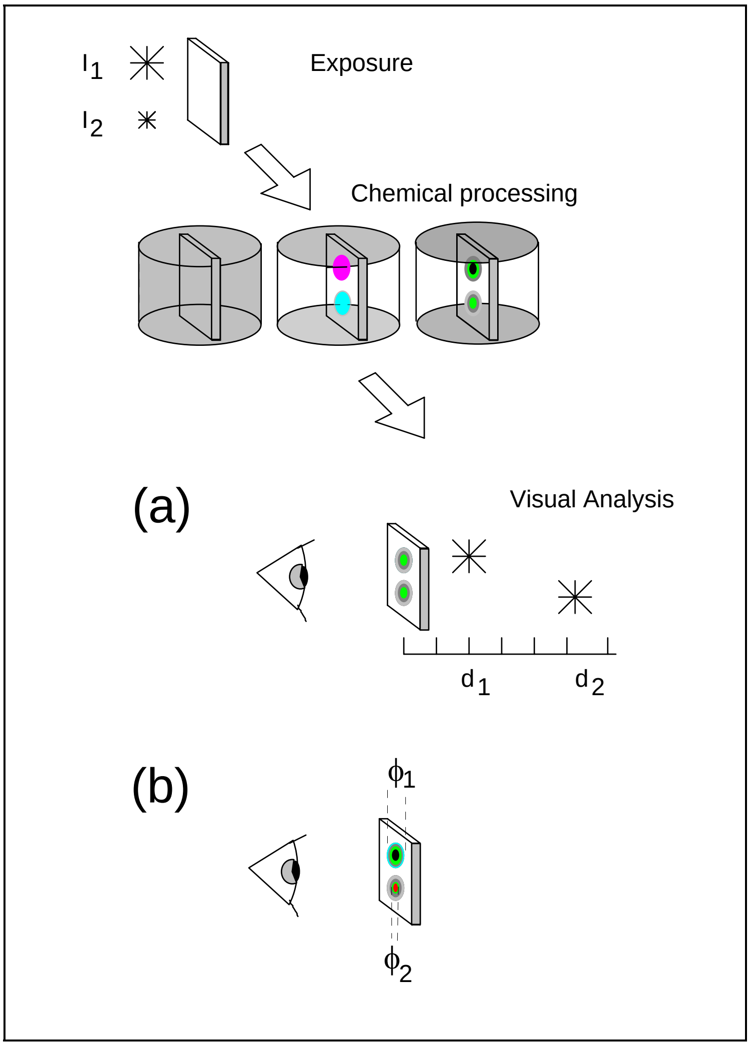

Fig. 12 Steps in a photographic/visual measurement of intensity. The intensities I_1 and I_2 are ultimately related to either (a) the distances d_1 and d_2 of a reference lamp on a photometric bench that produce the same apparent brightness through the exposed plate, or (b) the diameters ϕ_1 and ϕ_2 of the stellar image produced.

Photographic photometry benefited from the standardisation of plates, chemical formulations and conditions of development. Using such methods for laboratory spectroscopy, the precision of a measurement by the inter-war period had attained typically 5 to 10 per cent, or in optimal conditions about 1 per cent.[473] Although this is somewhat poorer than the visual determination of standard lamps, the measurement

[473]Dobson *et al.*, *op. cit.*, 14.

of the unstable and weak spectroscopic sources were correspondingly more difficult.[474]

A half-way house: photographic recording and photoelectric analysis

For astronomers, according to one historian, 'the development of recording microdensitometers, in some cases that could directly produce intensity records from the density, or blackening, in the non-linear photographic emulsion, was the important instrumental development'.[475] Such densitometers, or 'microphotometers', some employing photoelectric detectors, were in common use before World War I.

Before the turn of the twentieth century, a photoelectric cell was almost invariably a compound of selenium. The electrical resistance of pure selenium falls when illuminated, leading to its description as a 'photoconductive' material. In combination with other substances, selenium can be made to yield a small voltage (thereby acting as a so-called 'photovoltaic' device) when illuminated. The causes of this photosensitivity were unknown, and indeed of little interest, to those seeking applications.[476]

Another type of photosensitive effect was being actively investigated by the first decade of the century, however. The 'photoelectric effect' was the observation that certain materials, when used as a cathode in an evacuated glass tube, generated a weak electric current when illuminated with light.[477]

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[474] Claims of achievable precision could also be inflated. While 'under favourable circumstances results can sometimes be repeated to within one-fifth per cent', the American investigator C. H. Sharp gave 2% as the typical precision of commercial photometry, 'which is probably only approached in the best laboratories' [Gaster & Dow, *op. cit.*, 221].

[475] J. B. Hearnshaw, *The Analysis of Starlight: One Hundred and Fifty Years of Stellar Astronomy* (Cambridge, 1986), 419.

[476] For an examination of early investigations of selenium, see C. A. Hempstead, *Semiconductors 1833-1919: An Historical Study of Selenium and Some Related Materials* (PhD dissertation, Univ. Durham, 1977).

[477] The research is described later in this chapter. Practical applications of the photoelectric effect, in fact, preceded its scientific explanation.

The microphotometer was, in principle, simply a photometer incorporating optical elements to view a small portion of a photographic plate. The first such instrument was designed by Hartmann in 1899 for stellar photometry.[478] This was a visual photometer employing a variable-density wedge as the reference against which the photographic plate was compared. Experimenters made attempts to replace the eye by a physical detector within a decade. Koch, in 1912, used two sets of photocells, one illuminated directly by a small filament lamp, and the other receiving the light focused on and passing through the photographic plate. The ratio of the two signals, representing the fraction of light passing through the plate, was measured by a string electrometer. The replacement of the eye by photocells allowed Koch to automate the measurement process: the photographic plate was moved

[478] J. Hartmann, 'Apparatus and method for the photographic measurement of the brightness of surfaces', *Astrophys. J.* 10 (1899), 321-32.

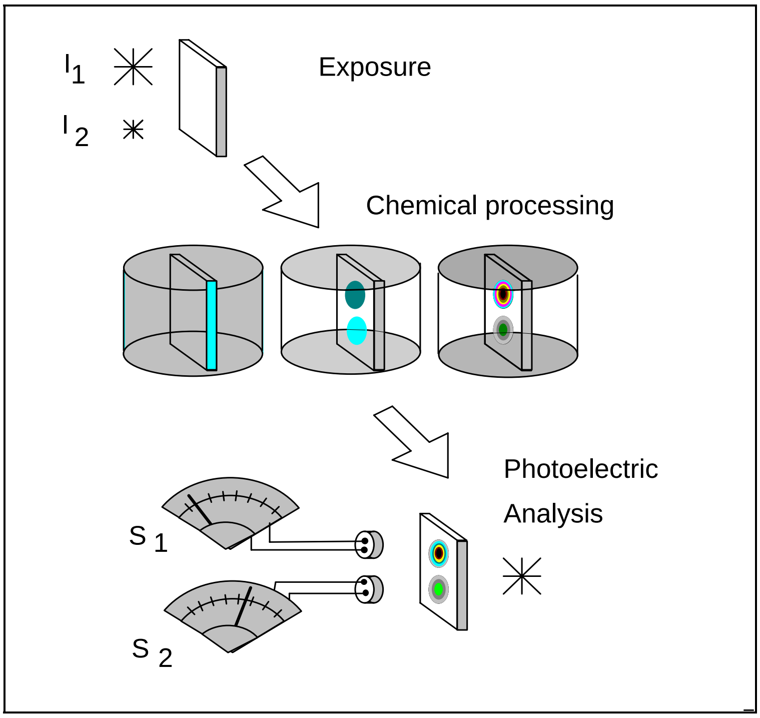

Fig. 13 Steps in a photographic/photoelectric measurement of intensity. The intensities I_1 and I_2 are ultimately related to the signals S_1 and S_2 of the photoelectric detecting system. The diagram is schematic only; for example, the photoelectric cells were usually phototubes consisting of an alkali-halide surface and anode connected with a large potential difference, surrounded by low-pressure gas and contained in a glass envelope. Intervening optical elements would be employed at both the exposure and analysis stages. The measuring instrument was typically an electrometer, or galvanometer operating on the null-balance principle.

through the focused beam by a clockwork motor, which also moved a photographic film used to record the deflection of the electrometer. Development of this film revealed a tracing proportional to the optical transmission along the original plate.[479] Such a system made feasible for the first time the conversion of spectrograms, with their collections of dark and light bands, into a graphical display of intensity variations. The stability of such early photocell microphotometers was not adequate for routine work unless used with great care by their designers. Koch's electrometer was prone to interference from stray electrostatic potentials, and the sensitivity of his photocells varied with time and temperature. A more successful instrument that found wide application among astronomers was the Moll microphotometer. This

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[479]P. P. Koch, 'Über die Messung der Schwäzung photographischer Platten in sehr schmalen Breichen', *Ann. Physik* 38 (1912), 507-22.

device used a thermopile instead of a photocell, a detector that benefited from good stability and sensitivity, and a longer history of successful usage.[480] This instrument was perhaps the first physical photometer to justify claims of superiority over the eye. Such was its indifference to external disturbances that, while in use, it 'did not require any special supervision'.[481] The portion of the photographic plate viewed could be made as narrow as 0.02 mm by slits, allowing extremely fine detail to be measured. The microphotometer was used by Moll's countryman Marcel Minnaert to produce the Utrecht solar atlas in 1939. Such densitometer recordings of spectra revealed much more information than the photographic records themselves: Minnaert found it 'a continuous joy to "read" these records and to recognise many features, well known from verbal descriptions but now, for the first time, seen in graphical representation'.[482] He cited the ability to record variations of spectral intensity directly as an important advance in practicality and precision.

Spectroscopists and astronomers designed and used recording microphotometers increasingly from the early twenties, with new designs being reported regularly in the journals.[483]

A 'more troublesome' method: direct photoelectric photometry

The opportunities for propagating error in the multi-step process of photographic photometry were recognised by the astronomers who practised it. Some of them made attempts to measure stellar intensity electrically almost concurrently

[480] The thermopile, a high-sensitivity variant of the thermocouple, had been in use since the middle of the previous century, and had figured in the precise blackbody measurements made at the PTR.

[481] W. J. H. Moll, 'A new registering microphotometer', *Proc. Phys. Soc.* 33 (1921), 207-16.

[482] M. Minnaert, *Astrophys. J.* 104 (1946), 331.

[483] For example: F. C. Toy & S. O. Rawling [British Photographic Research Association], 'A new selenium cell density meter', *J. Sci. Instr.* (1924), 362-5; K. S. Gibson, 'Direct reading photoelectric measurement of spectral transmission', *JOSA & RSI* 7 (1923), 693-7; E. A. Baker, 'A convenient photo-electric photometer and densitometer', *J. Sci. Instr.* (1924), 345-7; G. M. Dobson, 'A flicker type of photo-electric photometer giving high precision', *Proc. Roy. Soc.* A104 (1923), 248-51.

with photographic efforts.[484] Involving fewer components and processes, electrical methods promised better precision. Edward Pickering at Harvard College Observatory, who was to use visual techniques in his extensive astronomical surveys, performed some abortive trials using a selenium detector around 1877. In the early 1890s, George Minchin, an Irish professor of mathematics, experimented with photovoltaic selenium.[485] With William Monck, an amateur astronomer, he attempted in 1892 to measure starlight using a 7-½ inch refracting telescope without success, but they observed deflections of their electrometer due to the light from the moon, Jupiter and Venus.[486] Using more sensitive photocells three years later, Minchin reported observations on ten stars. Comparing the stars Regulus and Arcturus, he claimed favourable precision compared to the visual magnitude method. The size of the electrical signal was small, however: even for Regulus, a bright star, and employing the excellent light-gathering power of a 24 inch aperture telescope, Minchin measured a signal of only 20 millivolts at best, corresponding to a change of about 3% from the 'native' voltage of his photocell.

The experiments of Minchin and his collaborators went nearly unnoticed, and electrical detection of starlight was not attempted again until 1902, when Ernst Ruhmer in Germany observed eclipses of the sun and moon using a photoconductive selenium cell. Ruhmer's photoconductive cell was simpler than that of Minchin; it relied on the characteristics of selenium alone and so was not prone to oxidation of the liquid, which caused a consequent reduction in the magnitude and speed of electrical response. Five years later, Joel Stebbins (1878-1966) again tried selenium

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[484] See C. M. Huffer, 'The development of photo-electric photometry', *Vistas in Astronomy* 1 (1955), 491-8.

[485] G. M. Minchin, 'The electrical measurement of starlight. Observations at the observatory of Daramona House, Co. West Meath, in April, 1895. Preliminary report', *Proc. Roy. Soc.* 58, (1895), 142-54, and 'Observations. . . in January, 1896. Second report', *Proc. Roy. Soc.* 59 (1895), 231-3. His photocell consisted of a selenium coating on an aluminium plate immersed in (initially) acetone or (later) oenenthal in an air-tight glass tube.

[486] C. J. Butler & I. Elliot, 'Biographical and historical notes on the pioneers of photometry in Ireland', in: C. J. Butler and I. Elliot (eds.), *Stellar Photometry – Current Techniques and Future Developments* (Cambridge, 1993), 1-12.

as a detector.[487] He reported that he had 'met some of the difficulties which confront everyone who tries to work with selenium. Other agencies than light affect the resistance, and apparently no experimenter has solved, to his own satisfaction, the mysteries of this particular element'.[488] Stebbins found that the sensitivity improved twenty-fold when cooled, but the device was still relatively insensitive and the reading was prone to drift if exposed long to light or to air currents, which perturbed the temperature. The current used to measure the resistance of the cell also caused heating which decreased the resistance by some 10 per cent after a half hour, 'of the order of 100 times the light-effect from a bright star'.[489] Stebbins was able nonetheless to measure the intensities of some bright stars to a precision of about 0.02 magnitude (about 5%) using a 12 inch aperture telescope, 'results which are considerably more accurate than have ever been obtained by visual or photographic methods'.[490]

The experimental difficulties were nevertheless formidable. Despite Stebbin's claims, these early attempts with selenium were all unproductive compared to visual and photographic methods, and were generally ignored by the astronomical community. In 1910, however, Julius Elster and Hans Geitel, who had by then been experimenting with the photoelectric effect for over two decades, discovered a particularly photo-sensitive compound: potassium hydride. Two years later, Paul Guthnick at the Berlin Observatory used such a photocell to detect the light gathered by a 31 cm aperture telescope. With it, he was able to measure the intensity of bright stars reliably. As Pickering had found with his earlier visual work, the *quantity* of data could serve as a tactic to sway doubters. By 1917, Guthnick and a collaborator had made 67,000 measurements on 50 stars and planets by this method, making a special study of variable stars. On the advice of his associate at Illinois, Jakob

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[487]J. Stebbins, *op. cit.*, 185-216.

[488]*Ibid.*, 185.

[489]*Ibid.*, 187.

[490]*Ibid.*, 213.

Kunz,[491] Joel Stebbins, too, replaced his selenium photometer by a photoelectric version, noting a hundred-fold improvement:

> A comparison of the relative performances of the selenium and photo-electric instruments is somewhat difficult, but it is safe to say that with the new device, attached to the same 12-inch refractor, stars at least three magnitudes fainter can be observed than with the selenium photometer. . . the present measures of fifth-magnitude stars are better than the measures of any stars whatever with selenium.[492]

Such photoelectric observations were outside the domain of expertise of most astronomers. The German potassium hydride photocells were enclosed in glass tubes filled with low pressure argon, and supplied with a high voltage. Experimenters required expertise in chemistry, electricity and vacuum technology to make them. Operation was equally demanding. The output of the tube was measured by a delicate string electrometer suspended from gimbals, and mounted in a vertical orientation near the viewing eyepiece of the telescope where the photocell assembly was located.[493] Such mechanical detail, at least, was within the competence of the average astronomer. As to the measurement itself, the electrometer integrated the charge emitted by the photocell; the observer noted its deflection with a microscope and timed it with a stopwatch, and took the rate of deflection to be proportional to the brightness of the star.[494] The overwhelming practical difficulties associated with this

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[491]Kunz (b. 1874) had obtained his PhD at Zürich, and was responsible for bringing Elster & Geitel's technology to American attention.

[492]J. Stebbins, 'The eclipsing variable star, λ Tauri', *Astrophys. J.* 51 (1920), 193-9; quotation p. 194.

[493]Minchin and his collaborators, unlike their successors, had used a quadrant electrometer located in a room below the telescope. The mirror mounted on the electrometer rotor reflected light to a scale seven feet away, and was said to give reasonably consistent results in the isolated observatory building. This was fortuitous considering that the very small signal from the photocell was transmitted by fine uncovered copper wires. For a detailed contemporary description of the design and operation of such devices, see W. E. Ayrton, J. Perry and W. E. Sumpner, 'Quadrant electrometers', *Phil. Trans.* 182A (1891), 519-34.

[494]See, for example, W. F. Schulz, 'The use of the photo-electric cell in stellar photometry', *Astrophys. J.* 38 (1913), 187-91.

technique are evidenced by the fact that most of the early publications concentrated on methods rather than science.[495]

Guthnick used one of the first commercially available photocells; most other astronomers designed their own. In England, A. F. and F. A. Lindemann published the first account of the details of photoelectric apparatus and methods for astronomical photometry in 1919.[496] That the photocells responded differently to light than did the eye did not deter them; indeed, the Lindemanns marshalled it as a demonstration of the *success* for the new technology. They described the fabrication of photocells having potassium and caesium sensitive surfaces, noting that the two types could be used to measure a 'colour index' for stars. The potassium phototube responded most strongly to blue/violet light, while the response of the caesium type peaked in the yellow portion of the spectrum. The ratio of the two signals for a given star was an indication of the stellar temperature. Thus the astronomers recast the stumbling block of the illuminating engineers into a pedestal to extend their own observational grasp. They cautioned, however, that the new technology required some discontinuity with the past: because of the selective response to colour, they noted, 'it must be remembered that these magnitudes do not represent accurately either visual or photographic magnitudes, though they may be expected to approach the latter'.[497] The Lindemanns suggested a wide range of uses for photoelectric photometry, including measuring the variability of the sun, the albedo (surface reflectance) of the planets and brightness of the solar corona and sunspots.

Adequate sensitivity was a chronic problem. In 1920 Hans Rosenberg at Tübingen attempted to amplify the output voltage of his photocell using a triode valve, which allowed the electrometer to be replaced by a more robust galvanometer located away from the telescope. The poor stability of such early amplifiers, however, failed to convince other astronomers. Amplified photoelectric measurements did not become popular in the community until 1932, when a better

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[495] J. B. Hearnshaw, 'Photoelectric photometry – the first fifty years', in: Butler & Elliot, *op. cit.*, 16.

[496] A. F. & F. A. Lindemann, 'Preliminary note on the application of photoelectric photometry to astronomy', *Mon. Not. Roy. Astron. Soc.* 79 (1919), 343-57.

[497] *Ibid.*, 351.

design was developed by a member of Joel Stebbins' group.[498] This new amplifier was enclosed in an evacuated chamber to avoid sporadic fluctuations caused by cosmic rays, and amplified the photocell signal by over two million times. As one astronomer has written, 'the most successful early photoelectric photometrists were those who persevered with the intricacies of electronics at a time when electronic apparatus was generally absent from astronomical observatories'. He has noted also

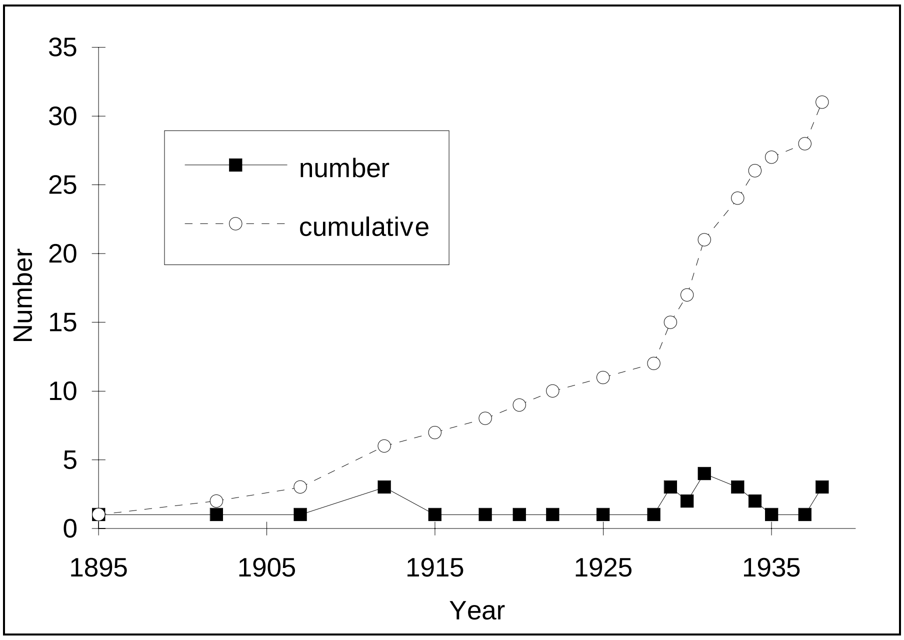

Fig. 14 Number of astronomical observers using photoelectric methods before the Second World War. *Source of data:* J. B. Hearnshaw, *op. cit.*, 19.

that the successful photometric astronomers before 1930 all collaborated with physicists who constructed or advised on the operation of their apparatus.[499] Stebbins, responsible for the first American group, complained in 1914 of the severe instrumental complexities to Harlow Shapley, who was considering taking up the technique:

> The whole problem is one of experimental physics, and our proportion of two physicists to one astronomer is about right. In fact I know of no man who has

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[498]A. E. Whitford, 'The application of a thermionic amplifier to the photometry of stars', *Astrophys. J.* 76 (1932), 213-23.

[499]Hearnshaw, *op. cit.* 18.

> the requisite training to make a photoelectric cell, mount it on a photometer, and finally produce results on stars.[500]

Photometric astronomy was thus a distinct branch of astronomy demanding unusual skills.

Despite the difficulties, interest in the photoelectric technique grew in the inter-war period, with over two dozen observatories in seven countries having attempted measurements by the end of the thirties.[501]

The general adoption of photoelectric photometry

As with photographic photometry, the photoelectric techniques adopted by astronomers were generally ignored by other photometric practitioners.[502] One reason for this was that the astronomical and electrotechnical communities were dealing with different domains of light measurement. Astronomers measured angularly small and dim light sources. The measurements were consequently imprecise, but could be used adequately to infer relative intensities, e.g. the fluctuations of variable stars. Electrotechnical engineers, by contrast, dealt with bright, large-area lamps. They demanded more precise measurements for comparing the technical performance of light sources. Also, as discussed above, the astronomers made an unproblematic transition from visual methods to physical photometry. For the purposes of illuminating engineering, however, the engineer was forced to consider the intensity as perceived by the eye; he was unable simply to dismiss the importance of the visual contribution. The difference in objectives between the two communities was reflected

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[500]Letter of Stebbins to Shapley, June 11, 1914, quoted in D. H. De Vorkin, 'Electronics in astronomy: early applications of the photoelectric cell and photomultiplier for studies of point-source celestial phenomena', *Proc. IEEE* 73 (1985), 1205-20.

[501]Hearnshaw, *op. cit.*, 17.

[502]One exception is the work of J. Kunz at the Nela Research Laboratory: in an early paper ['Photoelectric photometry', *J. Franklin Inst.* 182 (1916), 693-6], he noted that of the four lines of current research in photoelectricity (namely (i) the effect of frequency of light on electron velocity, (ii) the effect of light intensity on photocurrent, (iii) 'normal' vs 'selective' photoelectric effects and (iv) the influence of gases) the second had shown conflicting results by previous investigators. Kunz investigated the photoelectric effect as a photometric indicator and concluded that, with caution, it was a reliable technique.

in their limited inter-communication. There were only occasional contacts between astronomers and engineering photometrists.[503] Most importantly, physical methods were rejected because they worked poorly in practice; only with the inclination provided by a strong bias against visual methods and faith in the unsubstantiated promise of photoelectric technology would a practitioner persevere.

Some engineers were, nevertheless, willing to consider measurement without the human eye. For those not deterred by the seemingly unavoidable human contribution to photometry, physical methods proved tempting, if elusive. One early illuminating engineer lamented the impracticality of quantifying light, observing that 'it will be evident in the first place that we cannot, at least at the present time, readily expect to measure [the illuminating power of a light] *directly* by the movement of a pointer or by any mechanical means, as in the case of electricity, for instance'.[504] Another wrote in 1894 that 'if there were any outside reliable effects in nature which were functions of the actual brightness of light, as we feel it, we would have a photometric principle'.[505] The same engineer nevertheless rejected the only photoelectric detector available, the selenium cell, observing that 'of all things to exhibit the total depravity of the inanimate this stands first. The variation of its resistance is truly a function of the brightness, but on a curve which changes totally from day to day'. Selenium cells had been proposed sporadically for general light measurement from the late nineteenth century, perhaps first in commercial form as a photoelectric photometer marketed by Werner Siemens in 1875.[506] The unexplained drift of the resistance of selenium was a serious problem for those eager to exploit it.

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[503] One tentative link with astronomers was made by Edward Hyde, director of the Nela laboratory, and W. E. Forsythe in papers describing photometric standards of high-temperature sources and how they related to stellar measurements. See, for example, E. P. Hyde and W. E. Forsythe, 'The gold-point and palladium-point brightness ratio', *Astrophys. J.* 51 (1920), 244-51, and papers in 36 (1912), 114; 43 (1916), 295; 58 (1923), 294.

[504] J. S. Dow, 'The measurement of light and illumination', *Illum. Eng.* 1 (1908), 493-7; quotation p. 494.

[505] Barr & Phillips, *op. cit.*, 525.

[506] W. Siemens, *Nature* 13 (1875), 112. See also W. Siemens, 'On the influence of light upon the conductivity of crystalline selenium', *Phil. Mag.* 50 (1875), 416. Siemens' photometer replaced the eye with a selenium cell and galvanometer.

The drift problem was not immediately apparent to all investigators. Another early reporter on selenium cells was optimistic but not entirely accurate, reporting that 'light of all refrangibilities from red to violet is effective', and that 'a mere pin point of sensitive surface is as effective as a square centimètre.'[507] The convenience was also lauded:

> The use of the comparative or physiological photometer is irksome and demands some skill, while in the case of the selenium photometer the observation is reduced to the reading of a measuring instrument, and no special knowledge is required.[508]

Later investigators noted that such cells produced an inadequate voltage for deflecting an electrometer when illuminated with violet light. This made them unsuitable for colorimetric measurement, because researchers had established the importance of these extreme wavelengths on colour perception. Unable to respond to a colour to which the eye responded, selenium failed as a viable replacement for photometric applications. It still held some promise for physical measurements, though. A few die-hards remained enthusiastic, limiting their applications to the red end of the visible spectrum where selenium responded well:

> It has been established that selenium is capable of discovering differences of luminosity of the order of 1/100 per cent. This is an accuracy from 50 to 200 times that of the eye, and should add very greatly to the delicacy of all photometric processes. We have, therefore, tested the utility of selenium for discovering and estimating the difference in the amount of light transmitted by different glasses.[509]

Academic and national laboratory physicists familiar with radiometric methods began to extend their techniques to physical photometry. Like the illuminating engineers, there is little evidence that they had much contact with the

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The cell, exposed briefly to the sample light source and the reference light source, was used to judge equality of brightness. Thus, despite the variation of its resistance on extraneous factors, it could be applied like the eye to the matching of intensities provided that the intensities were not too different and were available in close proximity.

[507] G. M. Minchin, 'The photo-electric cells', *Astron. & Astrophys.* 11 (1892), 702-5.

[508] T. Torda, 'A portable selenium photometer for incandescent lamps', *Electrician* 56 (1906), 1042-5; quotation p. 1044.

[509] E. E. Fournier-D'Albe & E. O. Symonds, 'Some new applications of selenium', *Proc. Opt. Convention* 2 (London, 1926), 884-93.

astronomical community. Independently of astronomers, the physicists Nichols and Merritt devised a photoelectric photometer to analyse spectrographic plates. Speed was their motive: their instrument, incorporating a commercially obtained phototube from Germany, was used to make as many as 400 readings of plate transparency per hour.[510] Even more frequently than the newly available phototubes, thermocouples and thermopiles were used as detectors of visible light as well as heat.

Almost ignored by astronomers, the conceptual problem of adequately replacing the eye by an equivalent physical detector was broached by physicists. By the second decade of the century, the conjunction of a thermopile and a filter to screen out invisible radiation was being touted as an 'artificial eye'.[511] The central problem was to transform the spectral response of the radiometer (which responded almost equally to wavelengths over a very broad range) into a close approximation of the very uneven colour response of the human eye. Initial attempts employed liquid filters.[512] Practical problems, however, centred on the feeble response of such a system to visible light. 'The degree of sensibility required is very high', wrote one investigator, and hence the refinement of thermopile design and galvanometer sensitivity was severely limited.[513] He was to write sixteen years later that 'the possibility of using some form of radiometer as a substitute for the eye in photometry has been a long-standing dream', and evidently one not yet realised satisfactorily.[514]

The unreliable selenium cell was joined, in the second decade of the century, by the 'Thalofide' cell, a compound of thallium sulphide that changed resistance

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[510]E. L. Nichols & E. Merritt, 'A method of using the photoelectric cell in photometry', *Phys. Rev.* 34 (1912), 475-6.

[511]See W. W. Coblentz, 'The physical photometer in theory and practice', *J. Franklin Inst.* 180 (1915), 335-48, and H. E. Ives, 'A precision artificial eye', *Phys. Rev.* 6 (1915), 334-44.

[512]For example, one recipe for a 'luminosity curve solution' combined cupric chloride, potassium chromate, cobalt ammonium sulphate and nitric acid in water, contained in a 1 cm thick optical cell and kept at a constant temperature.

[513]Ives, *op. cit.*, 335.

[514]H. E. Ives & E. F. Kingsbury, 'The application of photoelectric cells to colorimetry', *JOSA* 21 (1931), 541-63.

when illuminated, and the phototube, a thermionic valve having a photosensitive cathode.[515] The former found only limited use in photometry, however, because it responded to infrared radiation more than to visible light. Physicists were drawn to particular physical detectors for the same reasons that they rejected the human eye: they could be understood more readily. Where the selenium and thalofide cells were unique flukes – unexpected discoveries – the phototube was based solidly on the photoelectric effect, which had been studied intensively from the first decade of the century. Contemporary theory was inadequate to explain the behaviour of selenium. Moreover, its characteristics were complex, depending on its purity, manner of preparation, type of electrical contacts, and past exposure to light.[516] Norman Campbell, then designing phototubes, contrasted them with nineteenth century selenium cells:

> From its first discovery, the change in the conductivity of selenium when illuminated attracted the attention of the inventor rather than of the theorist, to whom it long remained an isolated fact of no special significance. The photoelectric effect, on the other hand, is one of the corner stones of physical theory; but until recently its practical potentialities were entirely unrecognised outside the laboratory, and insufficiently recognised within it. While the immense literature of selenium is directed mainly to its use, in the yet larger literature of the photoelectric effect its use receives scant attention.[517]

Photoelectric devices had to be elevated, suggested Campbell, from mere components for inventors to the subjects of scientific research. He and his contemporaries in the 1920s saw opportunities for merging theory with new applications.

Photoelectric cells were a part of the new physics, rather than outside it, but they were as yet subjects of study rather than components in scientific apparatus. The unexplored complexities resisted their being employed as unproblematic elements in instruments. Campbell himself used the new technology for colour matching, intensity measurement and spectrophotometry. At the National Physical Laboratory after World War I, research into photoelectric photometry was considerably aided by

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[515] T. W. Case, 'Thalofide cell - a new photoelectric substance' *Phys. Rev.* 15 (1920), 289-91.

[516] Hempstead, *op. cit.*, 100-5.

[517] N. Campbell & D. Ritchie, *Photoelectric Cells – Their Properties, Use and Applications* (London, 1929), v.

collaboration with the GEC Research Laboratory, where former NPL staff were working. The director of the GEC lab, Clifford Paterson, had regular contact with his former subordinate John Walsh of the NPL through committee work. From 1924, when Norman Campbell at GEC headed a group developing photoelectric cells, the NPL Photometry Division was kept abreast of developments and received sample photocells to test. By 1925, this collaboration began to achieve results: the annual report mentioned

> use of photo-electric cells in place of the eye in a comparison of the light intensity of different sources; as a method of colour matching, the cell has been found, under suitable conditions, to give an accuracy ten times as great as the eye, but difficulty has so far been encountered in securing with the use of the cell the necessary sensitivity in the comparison of relative candle-powers of colour-matched lamps.[518]

Indeed, in the annual report the NPL staff expressed their indebtedness to the Director of Research at GEC, Clifford Paterson, and his staff 'for much helpful co-operation in the early stages of the work' and for the production of 'suitable photo-electric cells'.[519]

For straightforward photometry, the NPL investigators found the photocells to be 'no improvement' on the visual method, and definitely 'more troublesome'. Their initial researches used designs of test equipment and methods developed by Campbell and his group.[520] Despite being a 'corner stone of physical theory', photocells presented onerous practical problems. First, they suffered from 'photo-electric fatigue' caused by heating: the cells were one-tenth as sensitive at 50°C as at 20°C. Heating occurred when the cells were put into a reflective chamber (for measuring the integrated output of lamps) or even in a small unventilated room. Secondly, as astronomers had discovered two decades earlier, the photoelectric signal was small, requiring a sensitive (and delicate) electrometer to measure the emitted current. Various electrometers were tried, with the most successful being a design by

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[518]NPL *Report* (Teddington, 1925), 6.

[519]*Ibid.*, 6 and 107.

[520]T. H. Harrison, 'Preliminary note on the use of photoelectric cells for precision photometry of electric lamps', *Proc. Opt. Convention* 1 (London, 1926), 245-52.

Campbell. Attaining the necessary sensitivity and stability was difficult.[521] Third, the photocells did not produce a signal proportional to the intensity of light. This deviation from *linearity* of the devices depended on the wavelength of light, electrical supply conditions and other factors. The NPL workers avoided this problem by using photocells as they had the eye: the detectors were used to equate two light sources rather than to measure an intensity directly. Used in this way, only the *stability* of the response was important, and not the detailed proportionality.[522] The GEC group went further, developing a methodology to compensate for measurement drifts whether they were due to photoelectric phenomena or to the variabilities of human observation. Campbell emphasised 'establishing a scientifically accurate system of photo-electric photometry *in spite* of deficiencies of stability'.[523] The unreliabilities of the human eye were thus replaced by the different, but still considerable, variabilities of a physical detector. The problems of photometry were translated to a new, and as yet little explored, domain.

In the same year as the first success in the Electrotechnics Division, the Optics Division of the NPL was independently engaged in similar work. Its staff manufactured their own photocells to be used in a spectrophotometer. This was completed, and in regular use for colour standards work, by the following year. The stimulus for the research was the development of standards for the colours of railroad signal filters. In the post-war environment of restrained British innovation, this modest effort was appropriated as evidence for a burgeoning national optical industry: 'The work of the National Physical Laboratory is putting the whole subject of colorimetry and colour photometry on a firm foundation', wrote F. Twyman.[524]

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[521]NPL *Report* (Teddington, 1925), 123.

[522]This obviates the need for Campbell's 'class 3' measurement by restricting observations to 'class 2' comparisons. The linearity problem is discussed at greater length below.

[523]See N. R. Campbell, 'Photo-electric colour-matching', *J. Sci. Instr.* 2 (1925), 177-87.

[524]F. Twyman, 'The vitality of the British optical industry', *J. Sci. Instr.* 2 (1925), 369-80.

Adoption of the new photoelectric technology appeared unlikely to the NPL staff in the mid-1920s. The Photometry Division used the cells produced by their Optics neighbours, and tried making their own as well as testing GEC products. The group was finding that, while photocells could detect minute differences between two nominally 'matched' colours, this very characteristic of colour sensitivity made them unsuitable for light standards work. Seemingly identical incandescent lamps could have slightly different colours owing to glass contamination or to slight temperature differences caused by insulation of the base. Campbell at GEC tried different cathode materials, and optical filters in front of the photocells to make their spectral response more similar to the eye, with limited success. The NPL researchers tried filters of coloured liquids.[525] Campbell concluded that minor colour differences between nominally identical lamps would always unavoidably limit the precision of comparison to worse than 0.1%.

By 1927, the collaborators were experimenting with amplified signals, using thermionic valves. Even with cooled enclosures to reduce the 'photo-electric fatigue', drifts of the signal were troublesome, limiting precision to, at best, two to three times better than visual methods. In an attempt to improve this, they tried to switch rapidly between the reference lamp and sample lamp signals using two photocells, a commutator and amplifier.[526] The result was not a success, Walsh admitting that the best results still came from the 'original photometer' using a Campbell electrometer. Even so, 'in order to obtain results much better than those obtained with the visual photometer, every part of the apparatus needs considerable attention to ensure its perfect behaviour'.[527] The photometrist had been translated from meticulous observer to meticulous instrument minder.

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[525]NPL *Report* (Teddington, 1926), 132.

[526]In this technique, a mechanically-rotated switch (the commutator) alternately selected the reference and sample signals. The signal following the switch was thus a square wave with a 'peak' corresponding to the larger signal and a 'trough' corresponding to the weaker, and a frequency equal to the switching frequency. When the two components balanced, this fluctuating component disappeared. In principle, the amplifier could be 'tuned' to respond only to the commutator frequency and thus remove from the signal contributions caused by drifts and extraneous electrical noise.

[527]NPL *Report* (Teddington, 1927), 128.

By the next year, the group tersely reported that the ‘flicker method of photo-electric photometry’ was abandoned owing to ‘commutator trouble’, to be replaced by other more promising techniques. The NPL staff found that a ‘thermionic balance’ design, consisting of a photocell in a bridge circuit with a variable current source and detected by a micro-ammeter, could give precision of about 0.25%. The delicate electrometer still gave better results, however. Even so, they were able to report that ‘much more confidence has been established in the reliability of illumination measurements made with photo-electric cells’.[528] Echoing Airy’s attempt seventy years earlier, the NPL staff measured the change in illumination during a solar eclipse.[529] By the end of the decade, the staff were confidently designing more robust versions of their equipment for use in measuring the reflectance of surfaces and the diurnal variations of daylight.[530] The complications finally were being characterised and tamed.

By the end of the twenties, the NPL group had enough experience with photoelectric photometry to cautiously support its gradual adoption.[531] Writing of the future of photometry in 1929, John Walsh predicted instruments and standards of greater precision and a simplification of apparatus. Photometric precision had been stalemated since the turn of the century by the reliance on visual observation. Improvements would be needed for progress in other fields:

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[528]NPL *Report* (Teddington, 1928), 142.

[529]See NPL *Report* (Teddington, 1927), 137, and Staff of the photometry dept. of the NPL, ‘The variation of natural light during the total eclipse of the sun on June 29th, 1927’, *Illum. Eng.* 21 (1928), 198-202. They found the minimum illumination during the total eclipse to be 0.18 foot-candles, compared to a full-noon value of 3000 foot-candles. The Illuminating Engineering Society of N.Y. listed ten previous successful photometric observations of solar eclipses, dating from 1886. Half of these employed visual observation, one photography, and the remainder photoelectric methods. Photoelectric observations of eclipses were subsequently extended, e.g. C. H. Sharp, S. M. Gray, W. F. Little & H. J. Eckweiler, ‘The photometry of solar eclipse phenomena’, *JOSA* 23 (1933), 234-45.

[530]NPL *Report* (Teddington, 1929), 143.

[531]See, for example, J. W. T. Walsh, ‘Everyday photometry with photo-electric cells’, *Illum. Eng.* 26 (1933), 64-72.

> What is sufficient to-day may lag seriously behind even commercial requirements in ten or twenty years' time. Progress therefore is essential. Increased precision must be attained so that, in all that concerns the production and utilisation of light, progress may not be hindered nor development retarded.

From a subject that had shown little real change during his career, Walsh must have been impressed by the transformations provoked by photoelectric technology. *Progress* was the keyword, and it was linked firmly to physical photometry. 'Progress must necessarily lie in the use of physical methods'.[532] Walsh was not completely won over by the new light detectors, however. He saw the physical photometer as being analogous to a galvanometer, 'as a detector of minute differences, rather than as a measurer of integral illumination'.[533] Clifford Paterson, as head of the GEC research laboratory responsible for photoelectric photometry, was interested in promoting their commercial work even at the expense of denigrating his previous achievements at the NPL. Writing of the precision of visual methods he reminisced:

> If a greater accuracy than 2 or 3 per cent. was wanted, even under favourable laboratory conditions, it meant several repeat readings with more than one observer. If an accuracy of one-half per cent were required one sat down for a good week's work.[534]

The handful of supporters of photoelectric measurement in the twenties was to be swelled by many others a decade later, as commercial products began to appear.[535] Straightforward replacement of the eye by a photoelectric cell in visual photometers was a common project through the twenties.[536] The replacement was not without its difficulties, however; as at the NPL, complaints frequently surfaced that the new physical methods were not necessarily superior to the eye. One investigator warned

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[532]J. W. T. Walsh, *Photometry* (London, 1929), 8.

[533]*Ibid.*, 7.

[534]C. C. Paterson, 'Some thoughts on the international illumination congress', *Illum. Eng.* 25 (1932), 89-99; quotation p. 94.

[535]The commercialisation of photometry is the subject of Chapter 8.

[536]E.g. L. H. Tardy, 'Remplacement de l'oeil par la cellule photoélectrique sur les spectrophotomètres visuels', *Rev. Opt.* 7 (1928), 189.

that spectrophotometers ‘must be pushed to the extreme possible limit in order to yield data truly significant in specifying color stimuli.’[537]

Recalcitrant problems

As illustrated above, early twentieth-century photometry, like its nineteenth-century counterpart, was dogged by technical problems that limited its acceptance, impeded its application and restricted it to peripheral status. Where the experimental difficulties of the previous century had centred on the human observer, however, light measurement was now troubled by equally serious *physical* limitations. In contrast to the earlier hopes, light measurement could not be pegged straightforwardly to another physical quantity. For each community, the story of high expectations followed by the retrenchment of goals was repeated. In the words of sociologist Bruno Latour, the instruments resisted being ‘black-boxed’.[538]

Linearity

An important concern regarding physical photometers was the relationship between incident intensity and the resulting signal. The *linearity* (or lack of it) of physical detectors was important for some types of measurements. When the intensity of light was to be inferred from the position of a galvanometer dial, for example, the measurement relied implicitly on the assumption that the dial movement was proportional to the illumination. This assumption was frequently unjustified. The dial movement might rely, for example, on the precise winding of its electromagnetic coil, or the uniformity of the magnetic field of the surrounding magnet.

As with electrical phenomena, photographic recording had complications. The nonlinear nature of photography was explored in the last decade of the nineteenth century, principally by William Abney and the pair of investigators Ferdinand Hurter

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[537] I. G. Priest, ‘Note on the relative sensitiveness of direct color comparison and spectrophotometric measurements in detecting slight differences’, *JOSA & RSI* 19 (1929), 15

[538] B. Latour, *Science in Action* (Cambridge, MA, 1987), 2, 253.

and Vero Driffield.[539] They showed that the emulsion darkened as a result of chemical fogging and saturation of silver grains as well as by exposure to light. The result was a roughly *S*-shaped curve relating its opacity to the logarithm of light exposure. The mere recording of illumination could not, therefore, be used to infer intensity unless the photographic process had been calibrated carefully.

Some of the first post-war users of photoelectric cells believed that they had found a reliably linear method of recording intensity. ‘The current produced is proportional to the amount of incident light. . . which renders photoelectric photometry so valuable for measuring in absolute units the light received from objects’, wrote the Lindemanns in their account to astronomers.[540] Most astronomers, however, used their photoelectric photometers as comparators, interpolating an unknown stellar intensity between the intensities of two or more known stars. By the early 1920s, more extensive investigations of the characteristics of photoelectric tubes at GEC and elsewhere made it widely known that they could not be relied upon to yield a signal proportional to intensity except in very specific circumstances.

The usual method of dealing with problems of nonlinearity of response was to reduce the measurement to a process of comparison: the unknown quantity would be compared with a known reference. By simply observing the *balance* of two intensities – the equality of the instrument readings – factors such as amplification and the proportionality of the reading to intensity were avoided. As one industrial scientist put it:

> The traditional methods of making physical measurements. . . appear to imply that physicists as a body have a whole-hearted distrust of all types of instruments. Whenever possible, deflectional methods have been avoided and ‘balance’ or ‘null’ methods adopted so as to eliminate instrumental

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[539] V. C. Driffield, ‘The Hurter and Driffield system: a brief account of their photo-chemical investigations and method of speed determination’, *The Photo-Miniature* 5 (1903), 337-400.

[540] Lindemann, *op. cit.*, 344. There is evidence that the Lindemanns consistently underestimated the systematic errors in physical photometry. In the same paper, they optimistically wrote of a photoelectric photometer for measuring photographic plates, ‘provided they are not overexposed in any part. . . there seems every hope that one could combine the two methods with advantage’ [p. 317]. In fact, as their photographic predecessors were aware, photographic recording of intensity is inherently nonlinear.

> errors, and all essential instruments such as thermometers, or comparison standards such as boxes of weights or resistance boxes, have been calibrated with the utmost care before use.[541]

The criticism of nonlinearity was also levelled at early valve amplifiers. Since there was no guarantee that the output of an amplifier would be proportional to the input signal, distortion was the typical result. Amplifiers proved generally problematic for quantitative measurement. Again, compensation techniques were a partial solution. In describing a null recording colour analyser, a commentator noted that 'since equality of response to light from the two surfaces is indicated by no output from the amplifier, this method of recording is free from the usual objections which accompany the use of valve amplification for quantitative measurements'.[542] Another contemporary review reported a new instrument 'which combines the trustworthiness of the null method with the advantages of recording and rapidity of measurement'.[543]

Yet, in photometry, new industrial applications made null methods too complex and tedious: a dial 'visible at a glance' was needed. Careful calibration of individual instruments also proved costly. The last available option was to create stable, linear instruments, in which a voltage or current was reliably proportional to light intensity. One approach was to carefully determine the characteristics of photoelectric tubes, noting the range of light intensities and supply voltages that yielded a reasonably linear output, and then designing an instrument to operate within these limits. Another strategy was to avoid any amplification of the signal at all. Photovoltaic cells, which produce a voltage when illuminated, or photoconductive cells, for which the resistance changes, could be used with sensitive electrometers. Finally, in situations where a non-proportional signal was obtained from an instrument, the dial reading could be calibrated by a non-linear scale.

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[541] H. Moore, 'The influence of industrial research on the development of scientific instruments', *J. Sci. Instr.* 14 (1937), 41-6.

[542] R. C. Walker & T. M. C. Lance, *Photoelectric Cell Applications* (London, 1933).

[543] C. J. H., 'A new microphotometer for the recording of the blackening of photographic plates', *Rev. Sci. Instr.* 4 (1933), 553.

The spectre of heterochromatic photometry

The photometric problem *par excellence* of the 1920s was heterochromatic, or multiple-colour, photometry. Colour came pressingly to the attention of standards laboratories because of photometric standards. The availability of differently coloured light sources (gas flames, incandescent gas mantle lamps, carbon filament and other electric lamps) complicated the photometry programmes under way at the national laboratories. Owing to the unequal response of the human eye to different colours, it proved impossible to match the outputs or illumination provided by differently coloured lamps, or to specify the colour of any object unless the light source, too, was specified. This problem provided an incentive to put colour measurement on a firmer footing.

The expansion of photoelectric photometry was limited, too, by complications related to colour response. Photoelectric cells did not respond to light and colour in the same way as did the human eye. While the eye's sensitivity peaked for yellow light, photocells could be produced to peak anywhere in the visible spectrum between red and blue. Secondly, while the eye had an approximately logarithmic response to light intensity, photocells could have a linear or markedly non-linear response that varies with wavelength. This made the resulting signal not simply related to the either the subjective sensation or the energy content of light and colour.

An NPL physicist summarised the outstanding problems in photometry in 1924:

> The problems presented by the study of candle-power standards, flicker photometry, average visibility, and energy distribution must be solved before any further progress in photometry is possible, particularly as modern developments in high temperature radiations and spectral radiations seem likely to accentuate the existing difficulties to a very great extent. No reference has been made to physical photometry, as it seems that its basic problems are precisely the same as those of ordinary heterochromatic photometry, viz. average visibility, energy distribution, together with the technical problems of the sensitivity and reproducibility of whatever physical instruments take the place of the eye.[544]

Colour measurement and other problems thus plagued practitioners even while physical methods were being adopted. The physical method, he seemed to suggest,

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[544] H. Buckley, 'The field for international agreement and standardisation in illumination', *Compte Rendu CIE* (London, 1924), 408.

was a red herring and not a solution to photometry's problems. New technology was addressing new issues rather than facing the old ones.

The technologies of light measurement thus diverged and recombined between the turn of the century and the Second World War as practitioners hesitantly moved from a visual to a physical approach. Instigated by complementary convictions – that the eye was unreliable and that physical methods promised clear advantages – researchers sought a reliable method with limited success. By investigating photographic and then photoelectric techniques, they implicitly questioned the foundations of photometry and found them wanting. The defects of visual measurement were echoed in the complexities of photographic processing and of photoelectric amplification; the peculiar colour response of the human eye had its equal in the characteristics of photographic emulsions and photoelectric anodes. Despite the increasingly apparent analogy between visual and physical detectors, photoelectric methods rapidly came to dominate the subject. Nevertheless, the merging of technologies and the consequent programme to extend light measurement to new fields contained the seeds of problems. Colour could not easily be accommodated in a physicalist view of light. The renegotiation of the subject to standardise methods and to incorporate the measurement of colour is the subject of Chapter 7.

Chapter 7

Light and Colour Measurement by Delegation

After the First World War, appointed technical bodies increasingly determined the practice of light measurement. These groups evolved both from the technical associations discussed in Chapter 4 and from the government and business-supported scientific institutions treated in Chapter 5. For light measurement, which was increasingly directed and influenced by such organisations, committees and commissions became a primary source of change through the inter-war period. While involving many of the same individuals as did the associations and institutions, these new networks linked the ‘actors’ in different ways. In particular, these delegated bodies operated more often by consensus than by hierarchical decision-making, and were more goal-oriented.[545] More importantly, they were often heterogeneous bodies bringing together, for the first time, different scientific and engineering communities. This chapter traces the involvement of committees and commissions in the subject of light and colour measurement.

Technical delegations came to dominate the subject in the inter-war period. Their goals were matched closely to the aims of the government, industry and technical associations that created them. They also proved appropriate for solving the type of problem then facing the subject. In the post-war political climate, such technical panels were an embodiment of growing efforts to improve the co-operation of science and technology on a national and international scale.[546] The war had demonstrated the benefits of national organisation in and between technologically intensive industries; after the war, these concerns shifted from military to commercial competition. The new committees sought the consensual solution of pressing

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[545]*Committees* are, by definition, groups of people appointed to perform a specific task. *Commissions* are also groups charged with specific duties, but with the authority granted by a higher body, e.g. government.

[546]For the rise in internationalism before the war, and ‘international science without internationalism’ after it, see E. Crawford, ‘The universe of international science, 1880-1939’, in: T. Frängsmyr (ed.), *Solomon’s House Revisited: the Organization and Internationalization of Science* (Canton, MA, 1990), 251-69.

industrial problems, and the promotion of scientific activities by the rationalisation of standards. The situation for light measurement was a particular case of the increasing bureaucratisation of international science.

The case of colour measurement demonstrates how this new bureaucratisation operated. During the 1920s, the problem of quantifying colour came to the fore. The measurement of colour had previously gained little prominence within the communities concerned with light measurement, except where the photometric comparison of differently coloured lights was concerned. But coming to the attention of committees as a perceived hindrance to further progress in photometry, heterochromatic photometry opened the subject of colorimetry to different intellectual groups. Those most at odds proved to be communities of physicists and psychologists, which differed in their views on the nature, measurement and description of colour. A schism developed between proponents of physical measurement and supporters of a psychological view of perception. This was, in a sense, a recasting of the older, and seemingly resolved, play of visual *vs.* physical photometry for a new stage and new audience. The question of colour measurement was divisive for new associations of practitioners. Heterogeneous committees were forced to face these contentious issues soon after their formation.

The disagreements that developed around the subject, which could not be settled by the conventional methods of scientific closure, reveal the differing goals and methods of the protagonists. As sociologists Englehardt and Caplan have stated, ‘one must establish by negotiation formal procedures to bring closure to a scientific dispute when more than one community of scientists exists. . . or when a conclusion has not yet been reached by sound argument and one intends to engage in common activities or undertakings’.[547] For colorimetry, those procedures involved appointing committees that included different scientific communities to examine the subject. The ‘common activities or undertakings’ which impelled the ‘negotiations’ were an

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[547]H. T. Engelhardt, Jr. and A. L. Caplan, ‘Patterns of controversy and closure: the interplay of knowledge, values and political forces’, in: H. Englehardt, Jr. and A. L. Caplan (eds.) *Scientific Controversies: Case Studies in the Resolution and Closure of Disputes in Science and Technology* (Cambridge, 1987), 17. I use the term ‘closure’ in the senses they did, namely ‘a bringing to a conclusion’; ‘agreement’; or ‘closing of a debate by competent authority’ [p. 2].

abundance of commercial and utilitarian practices of colour matching and specification.

The initial attention of committees centred on the mundane questions of terminology. The problem of colour was, however, deeper than mere standardisation of jargon. Their members found themselves grudgingly broadening the scope of discussions to consider a wider range of phenomena while simultaneously narrowing the definition of what ‘colour’ was to mean in quantitative terms. Underlying that definition was a particular conceptual foundation of light and colour.

Committees proved to be central foci in the physical/psychological debate and in its eventual uneasy resolution. They brought together previously isolated communities to carry out a pragmatic agenda, namely the description and measurement of colour for industrial and scientific use. Colour measurement, then, was a problem substantially created and solved in the inter-war period by technical delegations. The solution, however, was a contentious one: colorimetry increasingly was appropriated and stabilised by physicists as a sub-category of photometry.

Commissions and committees are, more obviously than other forms of scientific interaction, a social response to social situations. In general, they bring together decision makers representing a range of expertise and opinion, or the members of other social bodies. With the members of such groups drawn from one or more cultural milieux, their activities concern social questions in the broadest sense. For this reason, the study of such organisations can probe the relationships between these cultures. Committees can also make explicit the connection between their subject and ‘external’ factors such as politics and the importance of key individuals. The organisation and membership of a committee depend on personal hierarchies and the status of various social groups. *Who* serves on committees, and *why*, can be as important as *what* they deal with, both for the results the committee achieves and for subsequent historical analysis. This is as true for scientific committees as for other types. Scientific commissions deal, in many cases, with the seemingly mundane topics of administration or regulation. But even such seemingly uncontentious agendas as measurement standards are influenced by social factors such as the domain of use of the measurement.

The product of a delegation is agreement on actions, reached by consensus or by the compromise of differing viewpoints. The decision-making bodies to be discussed here went beyond this conventional definition, however, in that they dealt also with *conceptual* questions. The commissions and committees defined not only nomenclature, but the very understanding and quantification of ‘light’ and ‘colour’. Social and intellectual factors merged through the medium of decision-making bodies.

The Commission Internationale de Photométrie

The first international body to concern itself with light measurement was the Commission Internationale de Photométrie. Its formation can be traced to the International Gas Congress held at the Paris Exhibition of 1900 attended by some 400 gas engineers and industry representatives, where a paper entitled ‘The photometry of incandescent gas mantles’ was presented. The conference chairman and President of the Société Technique de l’Industrie de Gaz de France, referring to the ‘general and common interest of producers as well as consumers of gas to be exactly informed of the lighting power of mantles employed for incandescent lighting’, proposed the formation of an international commission ‘to fix the rules to be followed in photometric observations of incandescent gas mantles’.[548] Meeting later the same day, the officials of the gas conference decided upon a constitution for the new Commission. It was to consist of four members each from France, Germany and Britain, and one each from Austria-Hungary, Belgium, Italy, the Netherlands and America.

The meetings of the CIP were held in Zurich, and its proceedings published in French. At the first meeting in 1903, delegates agreed to investigate the luminous intensities of the various flame standards in use. The next meeting, in 1907, included representatives from the national laboratories of Britain (NPL), Germany (PTR) and France (La Laboratoire Centrale d’Électricité, Paris), specifically to organise the inter-comparison of flame standards. By 1909, the work on standards had led to the

[548] Quotation of T. Vautier from J. W. T. Walsh & A. M. Marsden, *History of the CIE 1913-1988* (Vienna, 1989), p. 1 (my translation).

merging of the American, French and British candles into the *bougie internationale*.[549]

This early success in international co-operation encouraged a further expansion of contributions to the CIP. At the third meeting in 1911, the Commission asked each National Electrotechnical Committee to nominate members, swelling attendance by about 50%. The extension of the membership indicates a broadening of scope from the restricted photometric questions of gas standards to other aspects of lighting. The new delegates also brought a new perspective: the dominance and interests of the gas industry in the CIP were weakened because of the pragmatic reliance that the national laboratories had placed on carbon-filament incandescent lamps as the most reliable light source for comparison with the flame standards.

The inclusion of electric lighting was followed by further calls to extend the commission's mandate. During an International Electrical Congress held in Turin a few weeks after the CIP meeting, Leon Gaster, founder of the Illuminating Engineering Society of London, proposed the foundation of an international commission on *illumination*. The members of the CIP were polled, and they agreed to broaden the work of the commission to include the new goals.[550]

The Commission Internationale de l'Éclairage

The Commission Internationale de l'Éclairage (CIE) was formed in 1913. Instead of consisting of a few nominees of the national technical societies concerned with the photometry of gas engineering, the new commission included representatives from any country willing to form a national committee that was truly representative of

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[549] As noted in Chapter 3, German industry and science had adopted the Hefner lamp as the standard of brightness, with the PTR attempting to promote it as the international standard. Its difference from the other standards (the Hefner being about 10 percent weaker) and its wide usage made the German-speaking countries loathe to convert to the new international value.

[550] The transition from measurement of lamp *intensity* to *illumination of surfaces by lamps* was labelled the beginning of the 'quantitative age' by J. Walsh, 'The evolution of the lighting art', *Proc. IEE* 98 (1951), 309-15.

all organisations with a strong technical interest in lighting.[551] The change mirrored the commercial and technical shift in emphasis from gas to electrical illumination. Meeting every three years, the official languages of the commission were to be French, English and German. The object of the organisation was 'to study all questions relating to the industry of illumination and to the sciences which are connected with it, and to establish, by all appropriate means, international agreements on questions of illumination'.[552]

This early organisation was stillborn. The outbreak of the First World War soon after the meeting caused the abandonment of the international work in progress and the suspension of CIE activities.

In 1920, E. P. Hyde, who had polled support for the formation of the CIE eight years earlier, again made a European tour to gauge interest.[553] The first meeting of the reborn and restricted CIE was held in Paris in 1921. The German-speaking countries were not invited to attend, and proceedings were printed only in French and English.[554] The lack of German participation was part of a general situation in

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[551]The requirements for membership of a National Committee were 'rather detailed', so the statutes were modified at the first meeting in 1921 to encourage the entry of new countries 'where it was difficult to comply fully'. For those countries still unable to ensure a representative committee, observer status was granted. See Walsh & Marsden, *op. cit.*, p. 9.

[552]*Ibid.*, p. 7 (my translation). The CIE numbered its meetings consecutively with those of its predecessor, the CIP. Neither published its minutes or findings until the fifth session in 1921. The fourth session of the CIP/CIE had been cancelled at the outbreak of WWI.

[553]Hyde had long been prominently associated with American photometry, his career in many respects mirroring that of Clifford Paterson in Britain. Joining the NBS in 1903 to start its photometry department, he went on to head the newly established National Electric Lamp Association Research Laboratory in 1908. He was the chief organiser of the first regular university course on illuminating engineering, and was closely involved with the inter-comparison of flame standards. Hyde held the positions of representative of the CIP, President of the Illuminating Engineering Society of N.Y., and President of the American National Committee for the CIE.

[554]The attendance during the 1920s was dominated by French and English speaking delegates. For example, the fraction of French, British and American delegates was 82% at the 1921 meeting in Paris and 63% at the 1924 Geneva meeting, but only 52% at the British meeting in 1931, when Germany and Austria together

international science after the war.[555] Their attendance at international meetings and activities was boycotted. The membership broadened in the next meeting held in 1924, with Japan and Poland sending observers. The duties and attendance of the Commission sessions rapidly expanded.

The Commission Internationale de Photométrie had limited the scope of its activities mainly to the measurement of gas lighting, and to about a dozen delegates from its member countries. The new Commission Internationale de l'Éclairage took on a wider range of tasks, and opened its sessions to more national delegates and observers. As illustrated by Fig. 15, the number of delegates quickly enlarged, particularly in the period 1928-31. The number of topics covered also increased dramatically. Instead of organising a few days of meetings chaired by the President as its predecessor had done, the CIE separated the discussions into various technical meetings chaired by delegates from the member countries. This structure was further developed in the 1927 meeting at Bellagio, Italy, when delegates agreed that the field of the Commission's activities be divided into several sections, listed below.

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fielded 16% of the delegates, and other European countries were more strongly represented.

[555]Following World War I, Germany and Austria did not send delegates to the CIE until 1928. The exclusion enforced by the IRC was in effect during the formative years of the CIE, but was short-lived. German attendance at commissions such as the CIE, almost nil early in the 1920s, increased to about 85% of international meetings by 1926, when the IRC lifted its bar against the Central Powers. This correlates with the appearance of German delegates at the CIE meetings of 1928 and afterwards. See E. Crawford, *Nationalism and Internationalism in Science, 1880-1939: Four Studies of the Nobel Population* (Cambridge, 1992), 50. The political climate of international science between the wars is also discussed in, for example, D. J. Kevles, 'Into two hostile camps: the reorganisation of international science after World War I', *Isis* 62 (1971), 47-60, and P. Forman, 'Scientific internationalism and the Weimar physicists: the ideology and its manipulation in Germany after World War I', *Isis* 64 (1980), 151-80.

Table 4 Subject areas for the CIE agreed in 1927

1	heterochromatic photometry
2	definitions and symbols
3	lighting in factories and schools
4	automobile headlights
5	street lighting
6	coloured glasses for signals
7	diffusing materials
8	photometric test plates
9	precision of photometric measurements
10	light flux distribution
11	daylight
12	cinema lighting
13	glare

The successor to the CIP thus maintained many of the original objectives. Photometric (items 1, 2, 8, 9 and 10) and colorimetric (items 1 and 6) subjects occupied 6 of its 13 topics of interest. Each of these sections was to be assigned to a National Committee of one of the member countries. The officers resolved that each National Committee should 'make a special study of its specific subject and be responsible for the reports which will be presented at the subsequent Commission

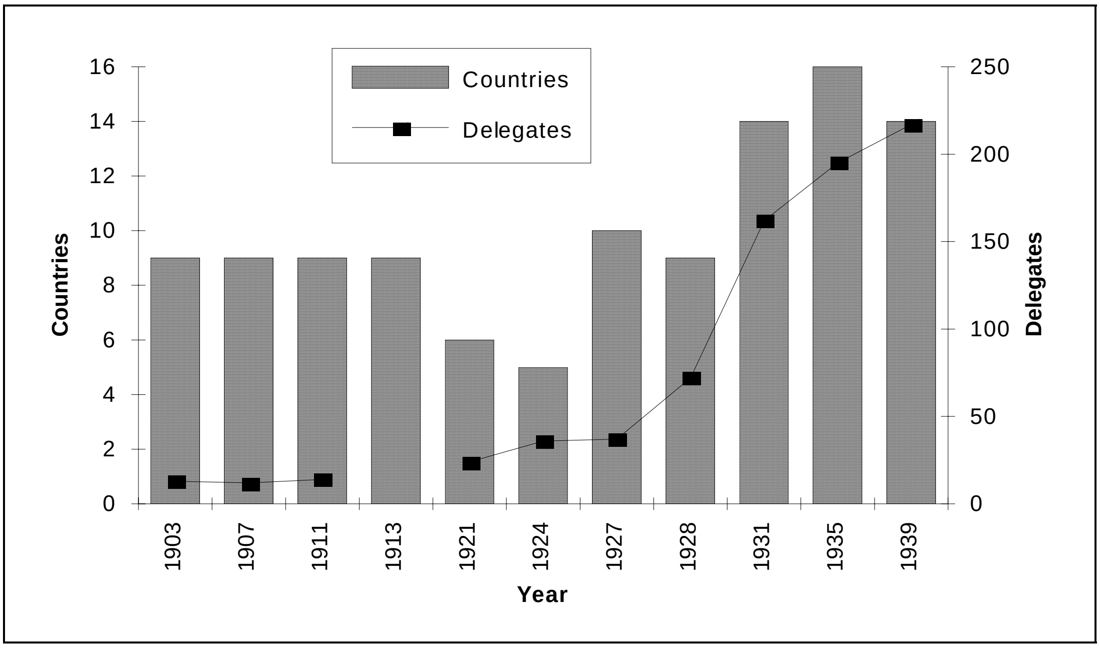

Fig. 15 Attendance of countries and delegates at the CIP (1900-11) and CIE (1913-39) sessions. The 1913 session was planned, but never held. Attendance at the 1939 session was reduced owing to the absence of Austria and Argentina. Because of the disruption of WWII, the Commission was dormant between 1939 and 1948. Sources of data: *Compte Rendu CIE* (1921, 1924, 1931, 1935 and 1939) and *History of the CIE 1913-1988* (Vienna, 1989).

meeting'.[556] The reasons for this division of subjects along national lines centred on practicality. According to N. A. Halbertsma, a Dutch illuminating engineer active in the CIE for several decades, this arrangement was formalised in 1927:

> experience had shown that these committees of specialists from different countries had a low efficiency because the members could not meet regularly and had to rely upon corrrespondence. Therefore an important change for the work between the session was decided upon. . . Each of the sections (or subjects) was assigned to the National Committee for that subject. It got the full responsibility for fostering on an international scale the study in that field and to maintain for that purpose contact with the other National Committees.[557]

The formation of national committees was modelled on the organisation and practice of photometry in each member country. Membership on the Commission was open to those selected by their national committees. Such committees generally chose a combination of individuals from those most active in the field, typically the

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[556]Walsh & Marsden, *op. cit.*, 10 (my translation).

[557]N. A. Halbertsma, 'CIE's golden jubilee', *Compte Rendu CIE* 15 (1963), 25.

presidents of national associations, academic scientists active in photometry, or representatives from national laboratories. The British and American representatives were drawn primarily from the national laboratories and industry. In Britain, the committee was generally a collection of representatives from the NPL, government departments, trade organisations, lamp manufacturers and instrument companies. Academic scientists were little represented.[558] These delegates represented the interests of commercial engineers, government scientists and standards organisations – a particularly productive mix that fairly sampled the active British light measurement community. The French committee was, in contrast, dominated by university scientists.[559] Its 'Secretariat Committees', responsible for studying a particular problem assigned by the Commission, were generally based at universities. The later German delegates fell somewhere between the two extremes, with industry, academe and national laboratories represented.[560]

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[558]'The National Illumination Committee of Great Britain is constituted by the Illuminating Engineering Society of Great Britain, The Institution of Electrical Engineers, The Institution of Gas Engineers, and the NPL, in co-operation with industrial, technical and professional associations and government departments interested in the subject of illumination' [*Illum. Eng.* 21 (1928), 106]. In 1927, 18 organisations and government departments were represented.

[559]Despite the formation of the Institut d'Optique and its journal *Revue d'optique théorique et instrumentale* in 1920, the industrial-scientific-governmental linkages in French optics were weaker than in Germany, although training was better organised than in Britain. The inter-war period saw a succession of government agencies tasked with the promotion of science and technology. See H. W. Paul, *From Knowledge to Power: the Rise of the Science Empire in France, 1860-1939* (Cambridge, 1985), 311-12 and 340-53, and M. E. W. Williams, *The Precision Makers: a History of the Instruments Industry in England and France, 1870-1939,* (London, 1994), 139-44.

[560]The figures for the two years for which delegate affiliations were listed are as follows: for the 1924 session, France sent six delegates, all but one academic; the U. K. sent nine, seven from industry and two from the NPL; the U.S. sent seven, of whom five were from industry and two from the NBS. In 1931, Germany sent sixteen, fourteen representing industry and one each from the PTR and university; France sent 29, eight of whom were academics, four from government and seventeen from industry; Britain sent 32, five representing government departments and two the NPL. For a discussion of the 'rapports inéxistants' between the physics community and industry in France in the inter-war period, see D. Pestre, *Physique et Physiciens en France, 1918-1940* (Paris, 1984), 238-41.

The division of studies along national lines was to be crucial to the development of the subject of light measurement. Each Secretariat Committee was ostensibly responsible for fostering international study in its particular field and for maintaining contact with the other National Committees through experts that each appointed. These technical committees were intended to discuss contentious questions in the three or four years between CIE sessions, 'hors séance. . . les questions *en litige*'.[561] In practice, however, such co-operation was limited. The various technical committees were typically kept busy with their national responsibilities at government or university laboratories, and had relatively little time to travel or to manage international co-operative work. The communications were further hampered by the physical distance separating the various groups. At the 1924 CIE session, for example, the delegates agreed to hold the next session three years hence in America. Owing to other commitments and the long travel time, most of the delegates found the plan impracticable, and they met unofficially in Bellagio, Italy, instead. Even this unofficial meeting was productive, leading to *Comptes Rendus* running to 1250 pages. A meeting was held in Saranac, New York, the following year. Several of the delegates found the sea voyage and fortnight of American travel a useful and unaccustomed venue for further discussions.[562] Despite this exception, the relatively brief personal contact at the sessions usually made detailed collaboration between the committees difficult. Furthermore, the volume of work to be presented soon meant that there was no time for papers by individuals to be

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[561] *Compte Rendu CIE*, 5th Session (London, 1921), 10, emphasis added.

[562] For example, Clifford Paterson, the President of the Commission, wrote, 'You will. . . appreciate how valuable is such an experience when illuminating engineers from all countries are thrown together for several weeks in informal relationship for study, instruction and recreation' ['Some notes on the meeting of the International Commission on Illumination in the United States', *Illum. Eng.* 21, (1928), 337-8]. Another delegate wrote: 'The sea trip from Southampton to New York gave time for recreation and for the final organisation of the British delegation. Mr Good [the President of the British National Committee]. . . probably curtailed many delegates' social programmes by dividing the party into groups responsible for various subjects, whose members met, often several times a day, to decide on their course of action at Saranac' ['A review of the proceedings of the 7th session of the International Commission on Illumination and the International Illumination Congress in the United States in 1929', *Illum. Eng.* 22 (1929), 167].

presented at the sessions. Instead, summaries were presented by National Committees. By the 1928 meeting, two or even three meetings of the technical committees met consecutively over the five days of the session. Contributions by individuals, when they were considered, were limited to semi-official venues. The host countries for some of the CIE sessions organised associated activities to demonstrate the state of the national industries, but which also promoted extended contacts between delegates and the sharing of information. At the 1928 Saranac meeting, ‘in order to make the trip to the United States. . . attractive to the European delegates’ there was an ‘Illumination Congress’ beginning three weeks before the official sessions with a series of technical visits to various American cities by chartered train, and culminating in the Annual Convention of the American Illuminating Engineering Society in Toronto, Canada. A similar Congress took place three years later for the Cambridge session of the CIE, with meetings and demonstrations held in Glasgow, Edinburgh, Sheffield and Birmingham. Coinciding with the centenary of Faraday’s discovery of electro-magnetic induction, it was a highly visible affair accompanied by the novelty of the flood-lighting of major buildings.[563] While the papers presented at these Congresses were published, they did not include the minutes of the discussion period as did the official proceedings. This arrangement of a series of meetings preceding the CIE sessions was an attempt to satisfy members interested in maintaining the CIE goal of providing ‘an international forum for all matters relating to the science and art of illumination’. Nevertheless, the meetings for individual authors were dispensed with at the 1935 Berlin/Karlsruhe session: instead, five days were devoted to discussing the results of 25 technical committees. While the work of some technical committees may have been communicated informally before the session, preprints and formal papers were not circulated beforehand. This abbreviated format of the CIE sessions naturally limited the amount of discussion possible, and made the acceptance of the proposals of the secretariat committees all the more likely. By the 1930s then, if not earlier, the CIE sessions were restricted to merely setting the questions to be answered by the technical committees assigned to particular countries, and for ratifying their

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[563] Flood-lighting had been employed at American war-time installations, and saw its first widespread commercial use in England in 1932.

conclusions. The *de facto* organisation of the CIE thus had evolved towards compartmentalising particular technical questions in individual countries. This arrangement was to be important to the foundation of colorimetric practice, discussed below.

The officers of this *illuminating* commission were individuals closely associated with *photometry* in their own countries, and mentioned in other contexts in this thesis. The proposer of the CIE was Leon Gaster, founder of the Illuminating Engineering Society of London. The drafters of its constitution included Clifford Paterson, then responsible for the Photometry and Electrotechnical section of the NPL; Eugen Brodhun of the PTR, co-inventor of the universally used Lummer-Brodhun visual photometer; and Edward Hyde, formerly of the photometry section of the Bureau of Standards in America and then director of the NELA Research laboratory.[564] By its first technical meeting in 1921, Paterson, Secretary and now director of GEC Research Laboratories at Wembley, was joined by John Walsh, his successor at the NPL, in the role of Executive Secretary, and Kenelm Edgcumbe, director and chief instrument designer for Everett Edgcumbe and Co., as Vice President. The ascendancy of individuals on the national scene was mirrored in the positions they assumed on the CIE. Paterson became President between 1927-31, and Walsh was eventually to succeed him for the period 1955-9.

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[564]Hyde, instrumental in gaining support for the Commission by visiting potential member countries, later gave up his seat on the founding committee to his former superior Edward Rosa (1861-1921), director of electrical research at the Bureau of Standards, and a man with a strong hands-on interest in light measurement there. See R. C. Cochrane, *Measures for Progress: A History of the National Bureau of Standards* (Washington, D.C., 1966), p. 110-11 and W. W. Coblentz, ‘Edward Bennett Rosa’, *Biog. Mem. Nat. Acad. Sci.* 16 (1936), 355-68. Photometry became an important part of Electrical Division for the first forty years of the NBS because of the attention gained by Rosa’s early investigations of electric lamps for the Government purchasing authority.

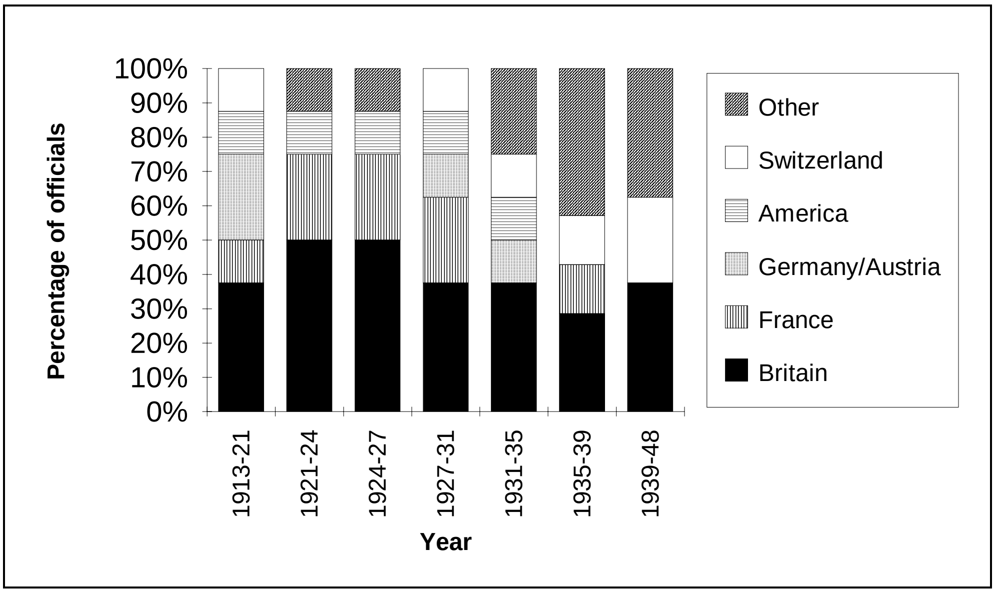

Fig. 16 Distribution of official CIE positions by country. Source of data: *History of the CIE 1913-1988* (Vienna, 1989), p. 61.

Although the CIE was based in Geneva, British influence was significant and continuous. The British officials held the most positions (typically one-third, as shown in Fig. 16) and typically for the longest durations. The Commission *Compte Rendu* was printed in England.[565]

The officers of the CIE seldom were prominent in their national committees. This was likely a choice by the individual for the higher-status and possibly less partisan international role provided by the CIE post. Paterson and Walsh of the NPL, for example, filled Commission posts, while members of British companies such as Edgcumbe were prominent in the British National Committee.

Legislative Connections

The work of the CIE was independent of, but loosely guided, legislation in its member countries. One of its first orders of business was to determine what laws or codes of illumination and light measurement were in effect. Although committees

[565]The 1913 plan for the CIE had called for the central office to be based at the NPL in Teddington, for which secretary and office space were being arranged at the outbreak of war.

were active in several countries, only America reported specific legislation.[566] By 1921 lighting legislation existed in six American states. This consisted generally of a lighting code prescribing illumination levels for factories, schools and streets, but in at least one state included fines for non-compliance. France had set up a commission in 1912 to study factory lighting, and a similar committee in Britain grouped policy-setting representatives of the Post Office and the Ministries of Health and the Interior. The latter's mandate included providing the government with 'information on photometric and economic questions'.[567]

The CIE organised committees to study technical questions that would allow international guidelines on illumination. These included committees on the lighting of factories, schools, and mines; street lighting; aircraft and train signals. The need to specify intensities and colour demanded that even more urgent attention be given to photometric practice.

The Construction of Colorimetry

As Table 4 indicates, the CIE placed the study and standardisation of colour high on its list of priorities. The interest in colour by the CIE was a reflection of work already underway in its member countries, particularly America and Britain.[568] Scientific investigation of colour measurement had been a recent development, however, dating barely from the First World War. The industrial need for colour metrics increased dramatically between the wars. In the British dyestuffs industry, for example, the production of dye colours rose four-fold between 1913 and 1927.[569] The scientific interest in the measurement of colour followed the establishment of professional societies, national laboratories, and the organisation of interested groups,

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566L. B. Marks, 'Législation de l'éclairage aux Etats-Unis', CIE *Compte Rendu* (London, 1921), 22, 204-21.

567*Compte Rendu CIE*, 6th Session (London, 1921), 23-4.

568See Chapter 5.

569R. Brightman, 'The dyestuffs industry in 1933', *Indus. Chem.* (Jan. 1934), 18-21. The tonnage of all colours was 4069 in 1913, 17,604 in 1927 and 22,045 in 1932.

especially in Britain and America. Between the wars, the subject was systematised and rationalised at these centres, and formalised through the CIE.

Compared with radiometry and photometry, colorimetry proved far more problematic for quantification in the inter-war period. Owing to disagreement between the interested groups, the nature of colour was debated in an unusually public manner, and finally agreed by compromise and uneasy consensus near the end of the decade. In a very real sense, colorimetry was 'constructed' to suit the views of members of that debate. The events illustrate how technical delegations grew to influence not only colour but the more general field of light measurement during the inter-war period.

Colour at the Commission Internationale de l'Éclairage

Although there was considerable work in colour taking place at a variety of institutions, companies and societies in America and Britain, by the early 1920s an international nucleus was beginning to form through the CIE. Unlike its predecessor, the Commission Internationale de Photométrie, the CIE tabled discussions of colour photometry from its first meeting in 1921, and faced the more fundamental problem of colour definition itself in its next meeting three years later. Unlike the national laboratories, the CIE was not initially concerned with questions of colour quantification. The commission was vitally concerned, however, with obtaining accurate *photometric* measurements, and practitioners now generally recognised these to be affected by questions of colour.

The first involvement began with a discussion of a subcommittee on the photometry of lamps, and the differing colours of various national intensity standards. The oldest extant standard, the German Hefner candle, had a distinctly red tint. The French, British and American standards were intended as interim standards until they could be related to a more fundamental physical standard based on the light emitted by a platinum surface at the melting point (a standard itself adopted in principle at the 1884 International Conference on Electrical Units and Standards).[570] This had proved

[570]The original suggestion had come from Jules Louis Gabriel Violle in 1881, and was taken up by Waidner and Burgess at the NBS. See, for example, H. T. Wensel, W. F. Roeser, L. E. Barbrow and F. R. Caldwell, 'The Waidner-Burgess standard of light', *Bur. Stan. J. Res.* 6 (1931), 1103-18.

difficult to achieve in practice, however, and so each of the national standards was based on electric lamps. The temperature of the filaments of these national sub-standards differed because the filament materials, construction and power consumptions had been differently specified by the individual laboratories. The result was a collection of national illumination standards of slightly differing colour. The investigators concluded that a comparison of differently coloured light sources was essentially meaningless unless the nature of the observer was also taken into account.[571]

The problem of intensity standards thus devolved to the fundamental question of whether to specify light intensity and colour in terms of its physical power or in terms of its effect on a human observer. And, since human eyes varied in colour sensitivity, how could 'the human observer' be defined?[572]

The CIE committee initially minimised the scope of its enquiry by proposing the use of colour filters to restrict the wavelength range, and so avoid the problems of

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[571] For example, an eye or detector sensitive mainly to red light would judge the relative intensity of a pair of light sources, one bluish and the other reddish, differently compared to an eye sensitive mainly to blue light.

[572] The even greater difficulties of determining the intensities of different coloured lights had not been obvious to all investigators. Pierre Bouguer [*Traité d'Optique sur la Gradation de la Lumière*, transl. by E. W. Knowles Middleton (Toronto, 1961), 49] noted 'A comparison of two lights of different colours in the way that we prescribe is chiefly embarrassing in case it is necessary to do it with more care, that is to say, when the two intensities closely approach equality; but there is a point where one of two lights will certainly appear more feeble. We have then only to take the mean between these two limits'. This technique of double-observation and averaging was promoted by the first illuminating engineers: 'It is true that with ill-devised apparatus and unsuitable methods some difficulties are experienced, but the judgement that two surfaces of different colours are of equal or of unequal brightness is an operation with which every artist in black and white or monochrome, and every engraver and etcher, is familiar' [A. P. Trotter, *Illumination: Its Distribution and Measurement* (London, 1911), 68]. The problem of differently coloured lights had been increasingly noted with the advent of the incandescent and arc lamps in about 1880. Some practitioners made two photometric measurements, through red and green glass, respectively. The standardisation of these filters then became a problem, with various schemes being suggested for preparing coloured solutions or 'screens'. The early confidence in the ease of colour matching had been further eroded by the experiences at standards laboratories in the first two decades of the century.

heterochromatic photometry.[573] The chairman deplored the lack of information, noting that ‘the physicists are behind the photometrists’ on the subject. Yet the delegates felt that the problems were not isolated to the study of colour. Discussion widened to the type of information needed. Would the description of colour be studied, or merely the physical question of the transmission of optical power by filters? The chairman admitted himself ‘a little frightened at the size and difficulty of colorimetric questions’. A committee on heterochromatic photometry (based in Paris) already existed, having been formed at the previous CIE meeting in 1921; should this be expanded to include colorimetry, or should a new committee be formed? The president of that committee, Charles Fabry of the Université de Toulouse, wrote:

> The problem posed by colorimetry is, in some respects, the inverse of that of heterochromatic photometry, since, in [the latter] case, it is proposed to characterise intensity by a number with no allusion to colour, whereas in the [former], one seeks to define colour without concern for intensity.[574]

In his opinion, the commission should concern itself with the physical side and ignore the psychology of colour. A Swiss delegate agreed, observing that colorimetry was too premature for international discussion. Instead, he suggested, the heterochromatic photometry group should first complete its study, then physicists in physical laboratories should ‘precisely treat the questions which must constitute the bridge between colorimetrists and physicists’.[575] According to this view, *physicists* would define the concepts which other practitioners would then employ. The CIE delegates, consisting of mainly scientists and engineers, were not eager to complicate their work with questions of physiology and psychology. Were they not in the midst of putting the subject of photometry on a *physical* basis? Yet other delegates wanted to broaden the scope of the CIE work. John Walsh of Britain suggested forming a new colorimetry committee having the freedom to study all aspects of heterochromatic photometry, colour description and the establishment of a standard of white light. The American Edward Hyde concurred, calling it a ‘question of high importance, and ripe for international investigation at present’. Rather than waiting to form a

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[573]*Compte Rendu CIE*, 6th session (1924) 28-38.

[574]C. Fabry, *ibid.*, 190 (my translation).

[575]M. Joye, *ibid.*, 31 (my translation).

colorimetry committee, '(which could find itself in contradiction to the heterochromatic photometry committee), it would be better to establish a collaboration between the two committees'.[576] Supporters of the two approaches separated into delegates involved with the existing heterochromatic photometry committee, based in Paris, and delegates from the Nela Research Laboratory and the NPL, who had little professional experience, but a strong interest, in colour measurement. The president, seeking compromise, noted that the two positions were 'well defined and not entirely incompatible'.[577] After deferring a decision until the final day of the session, the delegates unanimously voted to retain the narrow physical scope of the heterochromatic photometry committee, but to form a new colorimetry committee having one representative each from Britain and America.[578]

This episode, while narrowly escaping indecision, was the first formal tabling of a conceptual question that would occupy the next fifteen years, namely: can a workable system of light measurement be constructed by treating colour as a purely physical phenomenon, or must the observer be an intrinsic part of the system?

The American contribution to the CIE colour committee was inevitable, an American committee already having investigated the subject. A Standards Committee on Colorimetry had been established by the Optical Society of America in 1919 to set

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[576]E. P. Hyde, *ibid.*, 32.

[577]*Ibid.*, 32 (my translation). Although Fabry, chairman of the heterochromatic photometry committee, retained this position for an unusually long period in the CIE, the American contributions (from Crittenden of the NBS, and Hyde and Taylor of Nela) outweighed his reports by three to one. The differing views for a new committee cannot be seen, however, as a simple desire of the existing committee to retain control. Rather than wanting to explore all aspects of colour in an expanded version of the committee, the members wished to omit all question of colour measurement until they, and other physicists, had cautiously investigated practical techniques for removing its effect from photometric measurement. The two positions amounted to either including or excluding colorimetry from the study of photometry.

[578]Three members had been sought, but only two were proposed. The appointed members were Irwin Priest of the NBS and T. Smith of the NPL. Smith, the head of the Optics Division, was not present at the CIE Session. The proposers were unaware of the work already begun by John Guild of the Division, who performed all colorimetry work at NPL until Smith collaborated in the early 1930s.

forth terminology, summarise available data and to outline established methods of colour measurement.[579] Two years before the CIE meeting, the American committee had published a 69 page report attempting to formalise the measurement of colour. In it, they admitted to the provisional nature of what they hoped could become a science of colorimetry: 'the nomenclature and standards of color science are in an extremely unsatisfactory condition. . . manifest to practically all workers in this field'.[580] The work of the committee members had yielded a report which, 'being a more or less pioneer effort of its kind, must naturally be regarded as incomplete or tentative'. Indeed, the result was strongly disputed among the committee members:

> The definition of the term *color* which is advocated in the present report is the result of very careful consideration and protracted debate between various members of the Committee.[581]

The *protracted debate* concerned not the experimental data, but the concepts and language employed to discuss and understand it. The psychologists sought to express many aspects of colour perception that had hitherto been neglected.[582] The physicists,

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[579]Colorimetry Committee of the OSA, '1919 report of the Standards Committee on Colorimetry', *JOSA* 4 (1920), 186-7. Copies of the unpublished 50 page report were provided to parties who had expressed an interest in colour measurement, namely researchers at the NBS, Nela Research Laboratory, Cheney Bros., Johns Hopkins University, Dupont de Nemours & Co, Columbia University, Carnegie Geophysical Laboratory, and the Corning Glass Works.

[580]L. T. Troland, 'Report of Committee on Colorimetry for 1920-21', *JOSA & RSI* 6 (1922) 527 - 96; quotation p. 528.

[581]*Ibid.,* 531.

[582]Different problems preoccupied the psychology and physics communities. The psychologists' efforts to determine inner mental relationships between stimuli and perceptions contrasted with the physicists' goal of employing the visual response to measure external phenomena. The psychological dimension, which will not be elaborated here, approached that of the physicists most closely in the work of such 19th century investigators as Gustav Fechner (1801-1887), Wilhelm Wundt (1832-1920) and Francis Galton (1822-1911). See, for example, C. Ladd-Franklin, 'On theories of light sensation', *Mind* N.S. 2 (1893), 473-89. For a recent social constructivist history of psychology discussing the drive for quantification and the resulting 'methodolatry', see K. Danziger, *Constructing the Subject: Historical Origins of Psychological Research* (N.Y., 1994), especially Chap. 9. Regarding the simplistic metrology of human characteristics from an anthropological viewpoint, see S. J. Gould, *The Mismeasure of Man* (N.Y., 1981).

on the other hand, wanted to concentrate on properties of colour that could be reliably rendered into numerical form, even if that meant simplifying or idealising the complex characteristics of human vision. The American committee members were nevertheless more optimistic than the CIE committee to follow them:

> Practical colorimetry is. . . concerned with means for the unambiguous designation of those properties of objects and radiation which determine colour perception. Most of the means actually employed, however, utilize the visual apparatus as an essential element – in determining an equation of color – and hence the results are frequently not independent of the nature and special conditions of the apparatus. For this reason it is necessary, as in photometry, that the observers should be tested as average and normal.[583]

In 1924, the CIE adopted data performed at the NBS on 52 individuals aged under 30, measured in 'good lighting conditions', as a definition of the 'normal visibility curve'. The Commission recognised that this adoption was rather arbitrary, since different data would have been obtained with other observers, or the same observers measured under different conditions.[584]

American interest in colorimetry intensified after the 1922 OSA report. Helmholtz's *Treatise on Physiological Optics* was translated into English for the first time by the OSA; its second volume, devoted to colour perception, appeared in 1924. A reviewer noted that 'color vision at the present time is probably attracting a greater

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[583]Troland, *op. cit.*, 574. The very notion of an 'average observer', accepted without question by this time, was made possible by the eighteenth and nineteenth century realisations, particularly championed by Adolphe Quetelet, that human measures followed a normal distribution, and that "l'homme moyenne" could be discerned from statistical analysis. See A. Obserschall, 'The two empirical roots of social theory and the probability revolution', in: L. Krüger, L. J. Daston and M. Heidelberger (eds.), *The Probabilistic Revolution* (Cambridge, MA, 1987), vol II, 109-11; P. F. Lazarfeld, 'Notes on the history of quantification in sociology – trends, sources and problems', in: H. Woolf, *Quantification* (Indianapolis, 1961), 147-203., and I. Hacking, *The Taming of Chance* (Cambridge, 1990). The testing of groups, or 'collective subjects' during the inter-war period was associated with applied, rather than academic, psychology. See Danziger, *ibid.*, Chap. 8.

[584]By the late 1920s, several independent researchers had measured the 'visibility function' of human eyes, including Ives, Nutting, Coblentz and Hyde in America, Guild in Britain and Masamikiso in Japan. The CIE 'average' was a pieced-together combination of data from several of these sources. See, for example, P. K. Kaiser, 'Photopic and mesopic photometry: yesterday, today and tomorrow', in: *Golden Jubilee of Colour in the CIE* (Bradford, 1981), 29 and 31-2.

degree of attention both from the theoretical and practical points of view than ever before in its long history'. Describing its status, he also observed:

> it may be inferred that great difficulty has been experienced in completely harmonizing on any simple basis the extraordinary diversity of facts that must be explained consistently with each other.[585]

In Britain, John Guild at the NPL presented a one-man equivalent of the 1922 OSA committee report at the 1926 Optical Convention in London.[586] He echoed the American call for further research, and began to measure the colour response of human eyes. The Medical Research Council provided a grant to Imperial College for a research student, William Wright, to parallel and extend Guild's research. The good agreement between their results, which employed different apparatus and observers, convinced them and others of the feasibility of defining a 'standard observer'.[587]

In 1931, the American and British work entered the international arena at the meeting of the CIE in Cambridge. I. G. Priest of the NBS visited his co-member on the CIE colorimetry committee, Guild at the NPL. According to the NPL Annual Report, this 'enabled differences of view to be reconciled prior to the Cambridge meeting'.[588] The reconciliation was a hurried affair. Guild, having compared his and Wright's data late the previous year, had only recently finalised his ideas of a 'normal observer', i.e. an average human colour response. Seeking adoption of his methodology by the CIE, he lobbied members of the British and American committees by presenting a report to the Royal Society and sent copies to a few American researchers in the Spring of 1931.[589] Priest rallied by adapting the report and sending a written reply to Guild just two months before the CIE meeting. In it, he

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[585] Anon., 'Helmholtz's treatise on Physiological Optics Vol. 2', *JOSA* 11 (1925), 369-74.

[586] J. Guild, 'A critical survey of modern developments in the theory and technique of colorimetry and allied sciences', *Proc. Opt. Convention* I (London, 1926), 61-146.

[587] W. D. Wright, 'The historical and experimental background to the 1931 CIE system of colorimetry', in: *Golden Jubilee of Colour in the CIE* (Bradford, 1981), 2-18.

[588] NPL *Report* (Teddington, 1931), 15.

[589] Wright, *op. cit.* 13-17.

disputed that the British data were superior to earlier American results, but noted that he was willing to accept them. More importantly, the differences of view also related to the details of Guild's colour system, particularly his choice of three primary colours: 'not all countries. . . were prepared to adopt the NPL system of colour co-ordinates'.[590] The problem was that to produce certain colours, *negative* – i.e. unphysical – values of intensity were needed for one or more of the three component colours. Following a mathematical conversion to render all such sums positive, Priest accepted Guild's colour system. Because this agreement between the American and British committees occurred in the week before the CIE meeting, there was no time to print revised Agenda papers, and little opportunity for extensive discussion. Subsequently the CIE formally adopted the system, which included values for standard illuminants (coloured and 'white' light sources), numerical values for the visual response of a 'normal observer', and the mathematical relationships linking them. With these mathematical constructions, any colour could be expressed quantitatively.

The acceptance of the 1931 CIE standards thus can be seen as a result of conscious manoeuvring by the British and American delegates. Both Guild at the NPL and Priest at the NBS had restricted the subject of colorimetry to limit the importance of the human observer in the definition. Most aspects of colorimetry had *physical* bases: the definition of the 'white' and coloured illuminants; the method of calculating trichromatic co-ordinates based on the spectral transmission curves of the three primary filters; the method of converting between different trichromatic systems based on different colour filters. Only the highly artificial 'standard observer' – a table of numbers representing the response of a typical eye to the three reference colours – related this physical approach to visual perception. The acrimony in the subject through the remainder of the decade related to this restrictive *physical* definition of the subject.

The Commission's decisions on colorimetry were the highlight of the session, occupying eleven of the 24 pages of resolutions, and have arguably been the best-known and influential work of the CIE since. Industrial and national laboratories

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[590]*Ibid.*, 105.

welcomed the standardisation of a system of colour measurement, and began expressing colour information in the CIE terms. The activities of the Commission, however, waned for colour measurement. One highly likely reason for this is political. As noted above, the International Research Council's advocacy of policies of ostracism for German scholars between 1919 and 1926 had caused Germany to be unrepresented at CIE sessions until 1928, by which time the colorimetry committee had been assigned and work was well underway. France, too, was effectively excluded from participation in the colorimetry research by the decision of its delegates to support the opposing camp of heterochromatic photometry. As a result, while the British/American system of colour was accepted unanimously at the 1931 meeting, the German and French committees reversed their votes in the 'cooling off' period afterwards when national committees examined decisions.[591]

One participant later questioned 'why it was so much an Anglo-American concern', and decided that

> in the aftermath of the Great War. . . colorimetry cannot have had a very high priority in the European countries, and perhaps this helps to explain why France and Germany reversed their votes. They may well have felt they were being rushed into making decisions in a subject in which they were only just beginning to gain any practical experience of their own. They needed more time to think.[592]

So there was an impression that some countries were being railroaded into accepting an unsatisfactory compromise. Another reason for lack of effective action at the CIE after 1931 was its policy of rotating responsibility for Secretariat Committees. In sessions up to 1931, subject committees included representatives of several countries, even if most practical work was carried out in only one. In 1931 all committees were for the first time made the responsibility of individual countries. The subject of colorimetry was passed to Germany; colour specification and measurement were assigned to Japan. The American and British contributions were relegated to the

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[591]Enough other countries had nevertheless voted in favour for the system to become the international standard.

[592]W. D. Wright, 'The historical and experimental background to the 1931 CIE system of colorimetry', in: *The Golden Jubilee of Colour in the CIE* (Bradford, 1981), 2-18.

lighting of factories and schools, and to the lighting of mines, respectively.[593] The lack of effective international co-operation limited the range of the work performed. Moreover, neither the German nor Japanese researchers benefited from the combination of industrial and national laboratory support for colour research that had sustained the American and British efforts. The next session in 1935 included no report from Japan, and a relatively brief contribution from Germany filling in omissions from the earlier American and British work.[594] The colorimetry committee was not reassigned at the session, and no programme of work was requested for the following four years. At the following session in June 1939, the proposals of the German representative were rejected by America and Britain because they would have required changes to the rapidly developing colorimetric practice.[595] The CIE then reassigned Germany the colorimetry committee, but no work was begun before the outbreak of war. Thus active research in colorimetry returned by default to the ongoing national programmes in America and Britain.

By the early thirties, then, a complex network had grown of institutions, committees and individuals involved in the standardisation of colour measurement, as illustrated schematically by Fig. 17. In America, this network involved individuals working at large firms and at the NBS. The committees of the Optical Society of America served as the informal locus for this activity. In Britain, the NPL was the point of convergence for the DSIR-supported Research Associations. Internationally, the CIE attempted to co-ordinate and disseminate these efforts to the less active programmes of other, principally European, countries.

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[593] *Compte Rendu CIE,* 8th Session (London, 1931).

[594] *Compte Rendu CIE,* 9th Session (London, 1935). The Japanese delegation of seven persons did not table a paper or participate in the discussion periods; no record of their contribution appears in the minutes. The German work was limited to more careful definitions of a standard ‘white point’ using CIE colour co-ordinates, and the brightness of test surfaces.

[595] The German delegate, Dresler, recommended a new standard ‘illuminant E’, representing sunlight, to add to the existing three illuminants. Other delegates criticised its poor approximation to sunlight, the adequacy of the existing ‘illuminant C’ for this purpose, and the desirability of *reducing*, rather than increasing, the number of standards.

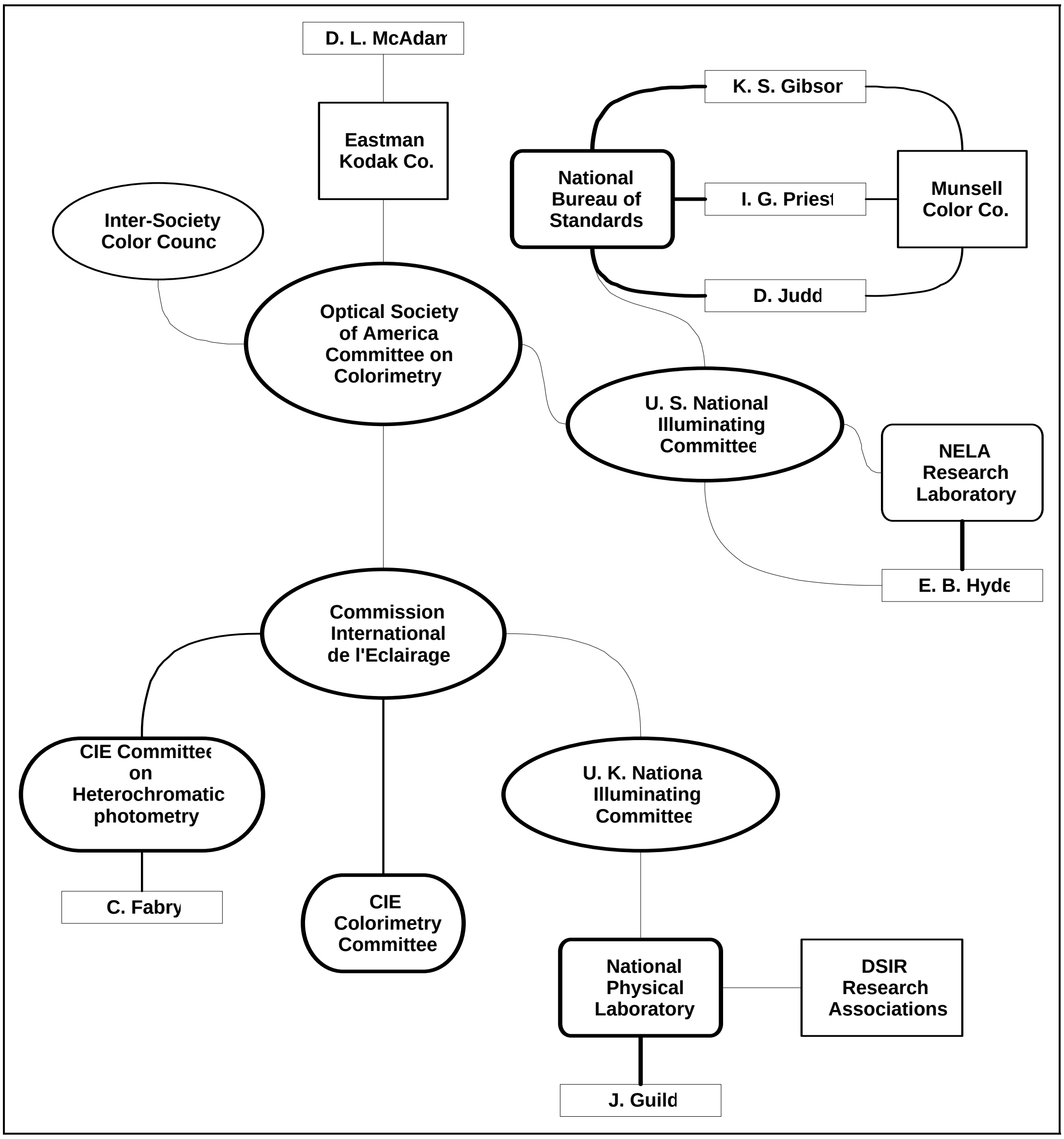

Fig. 17 Networks of colour measurement in the inter-war period in America and Britain. Thick lines indicate institutions employing individuals.

The restrained international collaboration in colour research after the 1931 CIE meeting was not reflected in American work. On the contrary, a second intensive phase of committee work started immediately afterward. A committee of its Illuminating Engineering Society was just then considering terminology and units for radiometry and photometry, and was extending this work to colour.[596] The American Committee on Colorimetry was also revitalised in 1932, when the Optical Society of

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[596] Anon., 'Illuminating engineering nomenclature and photometric standards', *Trans. Illum. Eng. Soc. (NY)* 25 (1930), 728-33.

America supported a more detailed examination of colour.[597] Another sign of continuing American activity was the birth of the Inter-Society Color Council, set up in 1931 to define colour designations for drugs and chemicals.[598] Irwin Priest 'had most to do with the form which the council took', restricting its domain of interest to standardising colour use in industry.[599] Not surprisingly, the ISCC defined its colours in terms of the Munsell colour notation, the product of the company that had sponsored NBS research associates.[600] The *de facto* industrial standard for colour matching in America thus derived from the company that had so actively supported NBS activities.

Changes in personnel also played a part in revitalising American colour research. In 1932, Kasson Gibson took charge of colorimetry at the NBS upon the death of , who had dominated colour research at the NBS for nearly two decades.[601]

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[597]D. L. MacAdam, personal communication, 4 Feb 1994, and Committee on Colorimetry, Optical Society of America, *The Science of Colour* (Washington, D.C., 1953), Introduction. The chairman, L. A. Jones, initially defined its purpose as being to 'introduce, advocate and facilitate use of the 1931 recommendations of the CIE'. Consisting 'almost entirely of industrial and government technologists', according to MacAdam, 'most members of the 1933-1953 committee had little experience with colorimetry.'

[598]See D. B. Judd & K. L. Kelly, 'Method of designating colors', *J. Res. NBS* 23, (1939), 355-85.

[599] D. Nickerson, 'The Inter-Society Color Council', *JOSA* 28 (1938), 357-9. The diversity of groups concerned with colour is illustrated by the council members, which included the American Association of Textile Chemists and Colorists, American Ceramic Society, American Psychological Association, American Society for Testing Materials, Illuminating Engineering Society, National Formulary, American Pharmaceutical Association, Optical Society of America, Technical Association of the Pulp and Paper Industry, and the United States Pharmacopoeial Convention. In the UK, the British Colour Council was set up at about the same time, and published a set of silk colour swatches as colour references in 1934.

[600]This American adoption of a proprietary colour system was not copied by other countries. The CIE and Munsell systems co-existed there, suggesting the decrease in internationalism through the decade.

[601]Priest 'spent many years of labor' on research into the specification of 'white' light, and 'left unpublished an exhaustive treatise giving the results of his studies and conclusions' [H. E. Ives, 'Irwin Gillespie Priest', *JOSA* 22 (1932), 503-8.

His successor had a perspective less centred on the physical approach championed by Priest and adopted by the CIE, and was more amenable to studying the perceptual dimensions of colour vision. The new OSA colorimetry committee, too, included a larger fraction of psychologists than did its 1919-22 incarnation.[602] Its original chairman, Leonard Troland, who also had died that year, was replaced by the physicist Loyd A. Jones.[603] The increased visibility of the psychological perspective altered concepts of colour by the end of the decade.

A lack of consensus

The widespread acceptance of the CIE standards for colorimetry masked a deeper problem with colour measurement. The measurement standards and nomenclature adopted by the NBS and the NPL were, despite earlier disagreements with researchers in heterochromatic photometry, essentially *physical*. The CIE standards combined the responses of seventeen British participants observing a two to three degree bright, plain visual field against a black background into a hypothetical 'average'.[604] This proved successful for simple colour measurements, such as the appearance of the light transmitted by colour filters. The limited modelling of human perception, however, made a wide class of colour measurement difficult. Surface texture, background interference, illumination level and a confusing assortment of other properties of coloured objects could influence the perceived colour.

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[602]The original committee had had five members, the two chief contributors being Priest and its chairman, Leonard Troland. Troland, a psychologist specialising in vision, had been the only proponent of a psychological perspective. The 23 members of the 1932 committee included 11 from industry, 4 from government, 3 from universities and 5 with unlisted affiliations, with roughly half espousing a psychological view.

[603]Troland (1889-1932), gaining a PhD in psychology in 1915, worked for two years at the Nela laboratory, and was elected president of the OSA in 1922-3 at the age of 33. In 1925, while holding an academic post at Harvard, he became Research Director of the Technicolor Motion Picture Corporation. See J. P. C. Southall, 'Leonard Thompson Troland', *JOSA* 22 (1932), 509-11. Jones, an associate editor of *JOSA* for over 25 years, specialised in the physics of photography.

[604]The data represented the mean measurements of ten observers measured by William Wright at Imperial College in 1929, and the seven measured by Guild from 1926 to 1928. See J. Guild, 'The instrumental side of colorimetry', *J. Sci. Instr.* 11 (1934), 69-78.

The use of a committee structure at the Optical Society of America and the CIE to study colour was a consequence of their constitutions. It also indicated, however, an essentially confrontational standpoint and aura of compromise for the subject. Upon the formation of the American committee on colorimetry in 1919, discord between its members had soon become apparent. The difficulties centred upon the nature of colour itself. In the original 1922 report of the committee, colour had been defined as:

> all sensations arising from the activity of the retina of the eye and its attached nervous mechanisms, this activity being, in nearly every case in the normal individual, a specific response to radiant energy of certain wavelengths and intensities.[605]

Colour was thus defined as a subjective concept rooted in a physical phenomenon. Implicit in this was the assumption that, neglecting physical differences between the eyes of individuals, colour was an invariant sensation common to all observers.[606] The idea of *sensation*, however, was being criticised in the literature of psychology. As early as 1893, William James, professor of psychology at Harvard University, had argued that a sensation – a conscious response to a physical stimulus – could not be realised except in the earliest days of life, because memories and stores of associations clouded the response.[607] Instead, psychologists by the twenties were expunging discussion of *sensation* and replacing it with *perception*, i.e. a stimulus interpreted by the brain in combination with other physical attributes.[608] This linguistic substitution represented more than mere terminology, but rather a conceptual shift away from attempts at measurement. Indeed, some psychologists sought to stem the tide by demonstrating that perceptions *could* be quantified:

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[605]Troland, *op. cit.*, p. 565.

[606]This assumption had been championed a half-century earlier by Helmholtz, but criticised as too ‘physicalist’ and simplistic by the proposer of an alternate system, Ewald Hering. Helmholtz’s theory found stronger support among physicists, while Hering’s was defended chiefly by physiologists and opthalmologists. See Turner, *op. cit*.

[607]W. James, *Psychology* (London, 1892), 12.

[608]L. T. Troland, ‘Optics as seen by a psychologist’, *JOSA* <u>18</u> (1929), 223-36.

> Psychology will never be an exact science unless psychic intensities can be measured. Some authorities [e.g. James] say that such measurement is impossible.[609]

Suggestions that colour be redefined in terms of perceptions caused complications. To the earlier definition in terms of the three attributes of *hue*, *saturation* and *brilliance* were added 'modes of appearance' such as *lustre*, *glow*, *gloss*, *transparency* and *body colour*.[610] The German psychologist David Katz concentrated on these perceptual aspects.[611] The Gestalt school of psychology included time-dependent effects such as *glitter, sparkle* and *flicker*. While such characteristics could be consciously experienced, they could not easily be reduced to physical terms. The majority of committee members rejected such additions to colorimetry. Instead, they attempted a return to a definition in terms of sensation, but restricted to non-spatial and non-temporal characteristics of visual sensation.[612] This limited the attributes to the original three. Such a definition was still unacceptable, though, to both psychologists, who mistrusted the concept of sensation, and to those who sought to measure colour by way of physical principles. The stalemate continued 'for more years than the chairman likes to remember' through 1937, when a proposal for photometric and radiometric terms was tabled. The committee members had reached agreement on nomenclature, which brought it closer to the usage of illumination engineers. Besides technical terms, though, another attempt was made to classify the concept and measurement of colour. Colour was relegated to the psychological category, while light fell in the psychophysical category and radiometry

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[609] L. F. Richardson, 'Quantitative mental estimates of light and colour', *Brit. J. Psychol.* 20 (1929), 27-37; quotation p. 27.

[610] Troland supported this approach when he noted 'the subjective study of color. . . in respect to those nuances which the German psychologists call. . . modes of appearance offers a fascinating field for investigation' [*op. cit.*, 233]. The Germans to whom he referred were David Katz (1884-1953), a Gestalt psychologist who specialised in colour perception, and Ewald Hering (1834-1918), a physiologist and psychologist. Katz's *The World of Colour*, espousing the psychological rather than the physiological or physical viewpoints, was first published in English in 1935, but was preceded by German editions in 1911 and 1930.

[611] D. Katz, *The World of Colour* (London, 1935).

[612] Committee on Colorimetry, *op. cit.*, 9.

in the physical category. ‘Slightly more than half’ the committee accepted this definition, with ‘no one. . . particularly pleased with the outcome’. This lukewarm compromise led the committee to explore a definition of colour as a psychophysical phenomenon. The chairman of the original committee, psychologist Leonard Troland, had earlier tried to marshal both the psychologists and physicists, writing:

> the term, light, is no longer used technically as an equivalent of radiant energy, whether or not the latter is ‘visible’. Light consists in radiant energy evaluated in terms of its capacity for evoking brilliance, when it acts upon an ‘average normal’ psychophysiological organism. Consequently, if we are interested to formulate psychophysical laws which have exclusively physical terms on one side of the equation, we must avoid the photometric concepts and use those of radiant energy, pure and simple.[613]

and later:

> Light can neither be identified with brilliance nor with radiant energy. It has the properties of both, taken together.[614]

A report on the psychophysical concept of colour was drafted by a few committee members in 1935. The reaction was ‘not in the least enthusiastic’ but a second report was prepared to investigate the idea more fully before it was finally rejected. This had a more promising reception by the committee, so again Jones appealed to various members to elaborate the psychophysical scheme. After the lukewarm agreement to the sensation-based approach in 1937, Jones in desperation assigned a recent PhD to the task. David MacAdam, a 28 year old physicist at Eastman Kodak specialising in human colour vision, tabled the third psychophysical report in 1938.[615] The content of the report straddled both the CIE 1931 conclusions and concessions to the psychological perspective. Its author noted that the draft was strongly influenced by Percy Bridgman’s *Logic of Modern Physics*, citing passages such as the following:

> Physics, when reduced to concepts [defined in terms of their properties], becomes as purely an abstract science and as far removed from reality as the

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[613]L. T. Troland, *Psychophysiology* (New York, 1929), 2, 57.

[614]*Ibid.*, p. 71.

[615]MacAdam was a research associate at Eastman Kodak from 1936, when he obtained his PhD. His association with the OSA began earlier, becoming a member of committees from the 1930s, Fellow in 1932, a director 1942-45 and President in 1962. MacAdam was later to trace the history of colour metrics from an unproblematic ‘internal’ viewpoint, in D. L. MacAdam, *Sources of Color Science* (Cambridge, Mass, 1970).

> abstract geometry of the mathematicians, built on postulates. It is a task for the experiment to discover whether concepts so defined correspond to anything in nature. . . . The new attitude toward a concept is entirely different. . . *the concept is synonymous with the corresponding set of operations.*[616]

This synthesis of two perspectives was not well received. 'A lengthy discussion indicated considerable dissatisfaction', but the committee members agreed to give it further consideration.[617] Over the next year, several suggestions for redrafts were made. The most significant of these were from Deane Judd of the NBS, who had from the beginning expressed a preference for the psychological definition.

The uncertainty about the subject, and the difficulty in achieving consensus, is illustrated by the large swings in committee opinion through the decade. The 1922 report had opted for a physical definition of colour. At the first re-evaluation of colour in 1932, the majority favoured a perception-based (psychological) approach, and its inherent complication of multiple colour attributes. In the reception of the first discussion paper detailing this concept in 1932, however, the members were split down the middle. The second attempt in 1937, reverting to colour-as-sensation and ignoring its many psychological aspects, passed by a slim majority despite redefining colour completely. Continuing unease among the members instigated the final attempt, defining colour as a psychophysical phenomenon. MacAdam's discussion paper, another significant change of direction, was accepted with less debate by the committee members, particularly after the public support by Deane Judd. In the end, the committee delegated Judd, the principal spokesman for psychology, and Arthur Hardy, representing the perspective of physics, to give final approval to the report.[618] MacAdam himself described the committee work as comprising 'long discussions, multilateral deadlock, and finally exhaustion'.[619]

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[616]P. W. Bridgman, *The Logic of Modern Physics* (London, 1927) 4-5, and D. L. MacAdam (1994), *op. cit.*

[617]Committee on Colorimetry, *op. cit.*, 11.

[618]A. C. Hardy, professor of physics at MIT, had promoted a physical basis for colour measurement from the early 1920s, when he designed and promoted his recording spectrophotometer.

[619]MacAdam (1994), *op. cit.*

The American committee took their hard-won definition back to the CIE in 1939. At the international level, acceptance by the CIE delegates was considerably easier, with no significant dissension. This can be attributed to the reduced interest in colour and the lack of meaningful international dialogue discussed above. The psychophysical concept of colour thus suffused into the international realm through the CIE. The debates were never reopened at the formal committees. In America,

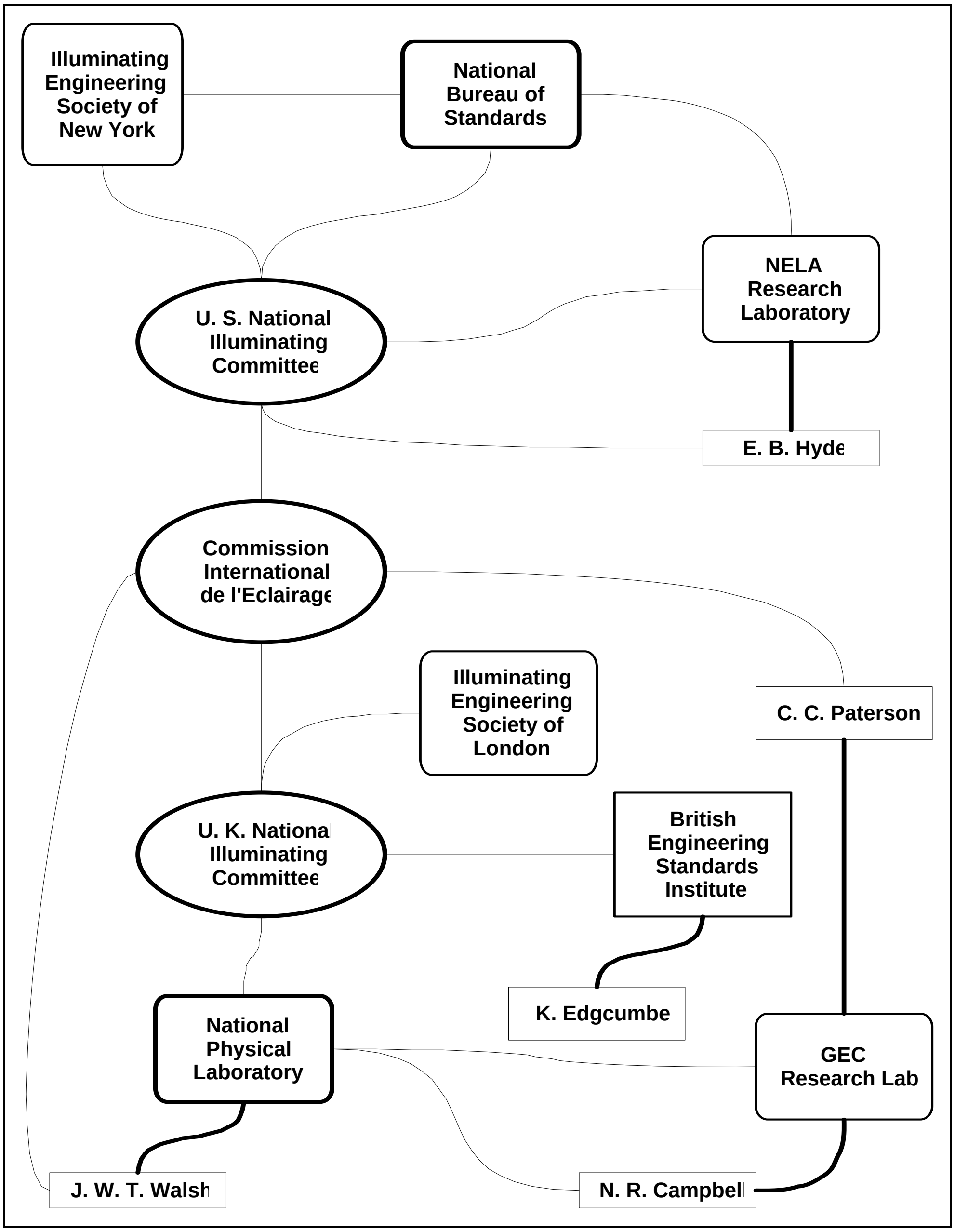

Fig. 18 Networks of light measurement in the inter-war period in America and Britain. Thick lines indicate institutions employing individuals.

however, there was evidence of disagreements between the physical and psychological camps into the early forties.[620]

The official merging of photometry and colorimetry at the NBS occurred in 1941 when, upon the retirement of the head of Photometry, J. Franklin Meyer, the then head of colorimetry, Kasson Gibson, took over both sections, a responsibility he held until the fifties. Following a long hiatus during the war, the Optical Society of America finally published its definitive book in 1953.[621] Its publication marked the end of controversy. The introduction, in which the debates of the thirties were sketched, was followed by nine chapters in which colour was expressed solely and incontrovertibly in psychophysical terms.

The history of colour measurement demonstrates the technical complexities and arbitrariness of definition faced in the inter-war period. On the one hand, there was an urgent practical need to develop a quantitative language of colour, illustrated by at least two highly successful empirical colour systems available commercially; on the other, a fundamental disagreement about whether to build the foundations of the subject on physics or psychology. Colorimetry attained the form it did as much because of contingent social circumstances as because of any inherent logical structure. During the period, colour measurement evolved in a direction opposite to that of photometry and radiometry. The networks of influence for light measurement shown in Fig. 18 are closely related to those for colour measurement shown in Fig. 17. Both include several of the same individuals and institutions (the NPL, NBS, OSA, CIE and Nela research laboratory) indicating their common roots. But colorimetry entered the national laboratories with a fruitful history of empirical application and relatively little theoretical content, while photometry and radiometry, rooted in physical measurement in the nineteenth century, struggled to be usefully

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[620] See, for example, a special issue devoted to the Munsell Colour System in *JOSA* 30 (1940). The editor noted that the first drafts of the published papers described two systems of fundamentally different underlying concepts, one for physicists and the other for psychologists, and that the authors had ‘aimed at reconciliation of opposing points of view’ (p. 573). As late as 1944, as reported by W. D. Wright in *The Measurement of Colour* (London, 1944, p. 55), evidence seemed to show that heterochromatic photometry could not be made to give consistent results.

[621] Committee on Colorimetry, *op. cit.*

applied to the industrial problems faced between the wars. By the Second World War, the methods and foundations of colorimetry had converged with those of photometry, both finding wide application in industry and consumer products. The conceptual foundations were still fragile, however, indicating the compromises and committee votes on which they were based.

The cases of photometric standards and colour measurement illustrate the central role played by technical delegations. For subjects whose scientific foundations were non-intuitive and contentious, committees defined limits and shaped content. Although goal-oriented, the delegations did not maintain a fixed investigative course. Launched by particular interests (the CIP by the gas industry, and the CIE by government support for illumination standards) the commissions nevertheless evolved in response to the experience of their delegates, the CIP shifting towards the photometry of electric lighting and the CIE undertaking colour investigations. And within these decision-making bodies, a handful of individuals proved to wield considerable power over the peripheral subjects they constructed: Leon Gaster and Clifford Paterson in shaping the early CIE; John Walsh and Edward Hyde in proposing the international study of colour; and Irwin Priest and John Guild in devising the CIE measurement system. The goals and membership of the delegations moulded the subject as profoundly as did experiment and theory.

Chapter 8
The Commercialisation of Photometry

Besides the technological and social aspects that had dominated earlier periods, light and colour measurement acquired an *economic* dimension in the two decades before the Second World War. During this period, practitioners increasingly *purchased* rather than *constructed* apparatus for the practice of photometry and colorimetry.[622] This change went hand-in-hand with transformations of the communities involved and of the subject itself. New manufacturers and users of photometric equipment emerged from, and modified, several existing communities. Technological innovation, too, introduced profound change, with much of the expertise in light measurement shifting from protocols of visual observation to the design principles of apparatus. The subject of light measurement became embodied in purchasable hardware, the culmination of a process that converted a human-centred activity into one manifested in instruments.[623] The spread of commercial instruments conferred a new legitimacy on the subject. There was thus a clear transition in the practice of commercial light measurement over this period. The industry expanded; the technology evolved; and, the number and types of practitioners increased.

Commercial development signalled a complex interplay of influences. Davis Baird has written recently that the period 1920-50 witnessed a 'scientific revolution'

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[622]The commercialisation of light measurement involved primarily goods rather than services. Although the national laboratories of Britain, America and Germany provided calibration and testing services, these were on a relatively small commercial scale and did not significantly influence the practice of photometry. At the NBS, for example, assuming the full gamut of standardising, candlepower and lifetime tests, the calibration of 1000 incandescent lamps brought in no more than $8,000 annually. For the companies and commercial laboratories using such services, photometric testing represented a small fraction of their operating costs. This chapter therefore concentrates on the commercialisation of hardware.

[623]This idea is similar to that of Gaston Bachelard's that instruments are 'reified theories' [*Les Intuitions Atomistiques* (Paris, 1933), 140].

in analytical chemistry because of the rise of instrumentation.[624] Contemporary chemists made the same observation; one, introducing a *Symposium on New Research Tools*, noted:

> it is particularly fitting that chemists and physicists should appear together . . . for the most remarkable aspect of the science of the past twenty years has been the way in which chemists and physicists have played into each other's hands. . . science and its tools develop together.[625]

Much of the change in analytical practice since the Great War can be correlated with the commercialisation of light-measuring instruments, particularly colorimeters and spectrophotometers. The availability of ready-made instruments for light measurement neatly removed a class of problems – the construction of apparatus – from the user and at the same time opened the subject to communities of practitioners that previously had not had contact with it. The new practitioners, in turn, influenced the course of light measurement. Robert Bud and Susan Cozzens have observed that 'new technologies can radically alter the access of a community of scientists to its phenomenon of study' and that

> people are an important element in spanning the institutional boundaries between the laboratory and the industrial firm. Scientists clearly do get involved in the development of instruments, in particular because of their ability to merge scientific and technical aims in the process of scientific work. Instrument makers, likewise, do interact with the laboratory as they develop and refine new products.[626]

This chapter expands upon their analysis, and details the interactions between user and maker. The work most relevant to the present study is that of Mari Williams, who has compared the scientific instrument industries in Britain and France up to World War II, particularly stressing the economic dimensions.[627] As will be demonstrated, however, the cause-and-effect relationship between the availability of technology and the evolution of practice is problematic and cannot be taken for granted.

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[624] D. Baird, 'Analytical chemistry and the 'big' scientific instrument revolution', *Ann. Sci.* 50 (1993), 267-90.

[625] Anon., 'Editorial', *J. Indus. & Eng. Chem.* 23 (1931), 1223.

[626] R. Bud and S. E. Cozzens, *Invisible Connections: Instruments, Institutions and Science* (Bellingham, 1992), xii-xiii.

[627] M. E. W. Williams, *The Precision Makers: a History of the Instruments Industry in Britain and France, 1870-1939* (London, 1994).

By 1930, the discourse of light measurement had shifted from questioning the *need* for quantification to the *instrumental means* of achieving it. This dialogue also took place in new contexts: in advertisements, in the evaluations of designs to be found in scientific papers, and in the 'New Products' pages of scientific journals. The growth of industrial and commercial markets for photometric apparatus had, in turn, cultural, scientific and technological consequences. New communities of practitioners became associated with light measurement, including commercial designers, industrial chemists and production engineers. These groups extended light and colour measurement to new applications demanding the development of new kinds of measuring equipment. With this new apparatus, scientists having had no previous concern with light measurement were able to apply the method to their particular problems. Particularly in industry, these early applications had mixed success. By the end of the decade, physical methods had almost entirely replaced visual observation, but the first flush of enthusiasm for the automated measurement of light in industry was fading.

The expansion of commercial light measurement thus involved the extension of the network of 'actors' to several new types operating at different levels. This chapter addresses the various issues in commercialisation by examining the two faces of the coin: on one side, the manufacturers of photometric apparatus, and on the other, the purchasers and users of such equipment.

Birth of a photometric industry

The fledgling photometric instrument industry largely grafted onto, and grew out of, a pre-existing scientific and precision instrument industry.[628] The commercial manufacture of light-measurement apparatus began on a small scale as soon as a

[628] The term 'scientific instrument', following a working definition by James Clerk Maxwell and widely accepted in Britain, specifically referred to a piece of apparatus designed for scientific experimentation. This excluded identical instruments made for commercial or utilitarian purposes such as photometers for gas inspectors. See D. J. Warner, 'What is a scientific instrument, when did it become one, and why?', *BJHS* 23 (1990), 83-93.

market, in the form of professional photometric laboratories, became established.[629] Commercial photometers proliferated, for example, after the passing of gas testing legislation, and again upon the introduction of electric lighting.[630] The competition between gas and electric lighting systems, in particular, caused a flurry of development.[631]

By World War I, the sale of photometric devices was a stable if small-scale enterprise. In America, the war triggered an upswing in the instrument industry. The

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[629]Such growth is notoriously difficult to document. Reliable figures for the numbers of products available, quantities sold and prices have not been amassed. In the absence of such data, growth has been inferred from references in contemporary publications.

[630]See, for example, W. J. Dibdin, *Practical Photometry* (London, 1889) and J. Abady, *Gas Analyst's Manual* (London, 1902) for a range of British products for gas testing.

[631]Appendix I illustrates the rise in photometric publications in the 1880s consequent upon the commercial availability of electric lighting. The appropriate *type* of photometric measurement was contentious; gas and electric lighting generally produced a different distribution of illumination on horizontal and vertical axes. Quantities such as 'mean horizontal candlepower' and 'mean spherical candlepower' were increasingly measured by purpose-built commercial instruments [by 1925, with the dominance of electric lighting established, only mean spherical candlepower was much used, mean horizontal candlepower 'now recognised as having little or no meaning' [Anon., 'Cube photometer', *J. Sci. Instr.* 2 (1925), 201].

Fig. 19

Early comme … o. Despite the apparent variety of f

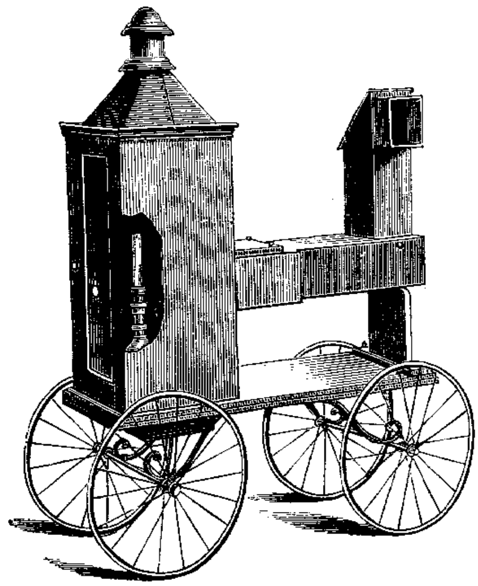

FIG. 14.—SUGG'S TRAVELLING PHOTOMETER.

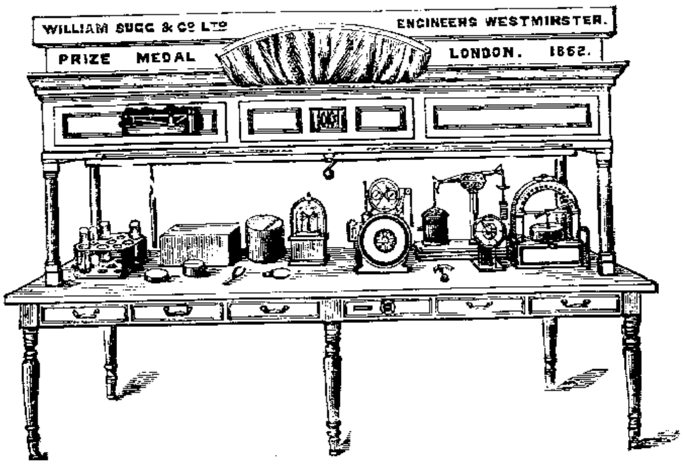

FIG. 5.—CLOSED EVANS PHOTOMETER.

Practical Photometry: A Guide to the Study of the Measurement of Light (London, 1889), pp. 29, 34, 68].

heavy reliance on European instruments existing before the war was rapidly reversed. 'We now manufacture over 85 per cent of our industrial and scientific instruments and appliances,', wrote the director of the NBS in 1924, 'where before the war over 80 per cent of these were imported'.[632] The instruments included light-measuring devices such as photometers, spectrophotometers and colorimetric apparatus. Far from being merely the adaptation of designs originated by academic or government scientists or

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[632] G. K. Burgess, quoted in Cochrane, *Measures for Progress: a History of the National Bureau of Standards*, 269.

the copying of European apparatus, this activity involved research, development and manufacture proceeding in parallel and often within a single company. As discussed in Chapters 5 and 6, commercial research laboratories played an important role in the development of light measurement during the 1920s. By the late thirties, an American government survey listed at least four companies with significant numbers of staff active in research on light measuring instruments.[633]

The war caused a similar expansion of the British precision instruments industry.[634] With the creation of the Ministry of Munitions in 1915, instrument firms were expanded, redirected or re-sited to meet the requirements of military instruments. When the war ended and government contracts were withdrawn, many companies found themselves overextended in production capacity compared to the available markets for their goods. To encourage research and co-operation between firms, the newly founded Department of Scientific and Industrial Research supported the formation of the British Scientific Instruments Research Association (BSIRA) in

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[633]These were: Bausch & Lomb in Rochester, N.Y., researching photometers and spectrophotometers with a total of 46 staff; the General Electric Incandescent Lamp Laboratory at Nela Park, Cleveland, employing 47 engineers and scientists and 59 support staff in the engineering and lighting research labs, where research included ‘spectrophotometry, photometry, physical, biological, physiological, photochemical and psychological aspects of light utilization; the science of seeing, and many phases of color’; the Westinghouse Electric and Manufacturing Co. (East Pittsburgh, Pa) Lamp Division in Bloomfield, N. J., where the Engineering Dept employed 108 staff including 34 engineers studying photometry and physical measurements, and its Research Dept. employed 15 for research including photoelectricity and spectroscopy; and, the Weston Electrical Instrument Corp. employed 30 staff to ‘develop instruments for measuring electrical. . . means for measuring light. . . and any quantity which can be made a function of an electrical quantity’. See C. Hull, ‘Industrial Research Laboratories of the United States, 6th edition’, *National Research Council Bulletin No. 102*, (Washington, D. C., 1938), pp. 33, 90, 222 and 223. This survey undoubtedly underestimated the amount of research being performed, asking the companies themselves to judge whether their work was research or merely ‘the improvement and development of products’. The efficiency of data collection is also uncertain: some 454 of the 1769 companies ‘for various reasons did not find their way into’ the 1933 edition.

[634]M. Williams, ‘Crisis or complacency? The precision instrument industry in Britain and France, 1900 - 1920’, in: Blondel *et. al.*, *op. cit.*, 273-81.

1918.[635] Nevertheless, government initiatives played a minor role in the commercialisation of light measurement.

The expansion of the photometric instrument industry was a direct response to the needs of practitioners who were unable or unwilling to design and construct their own equipment. Several factors determined these user requirements: the development of research programmes, the increase in routine light measurement, and a rise in appreciation for the benefits of quantitative light measurement.

This motive for the early expansion of the industry is at variance with conclusions drawn recently by Yakov Rabkin, who suggests that the integration of instruments into science 'occurs through vigorous supply of advanced instruments on the part of industry'.[636] As I shall illustrate, the 'supply of advanced instruments' as an impetus to change was a feature of the early 1930s and beyond, but not of the preceding period. Indeed, the case of light measurement closely follows the four stages in the development of new instruments suggested by the National Academy of Sciences in America:[637]

1) discovery of suitable means of observing some phenomenon,
2) exploration of this phenomenon with special, home-made instruments or commercial prototypes,
3) widespread use of commercial instruments,
4) routine applications of the instrument to control industrial production as well as research.

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[635]This initiative attracted member firms specialising in either optical, electrical or *x*-ray instrumentation and had limited success. The organisation continued with government support (owing to its identification as a 'key' industry) through World War II. While becoming peripherally involved in the design of photometric instruments, the association was of little importance to the commercial development of the subject in Britain. For details of the activities of BSIRA, see Williams, *op. cit.* [6], 85-9 and 123-36.

[636]Rabkin, 'Rediscovering the instrument: research, industry, and education', in: Bud & Cozzens *op. cit.*, 66.

[637]National Academy of Sciences, *Chemistry: Opportunity and Needs* (Washington, D.C., 1965), p. 65, quoted in Rabkin, *ibid.*, 66.

That is, the spread of instrumentation was mediated as much by users as by manufacturers. Stage (1) and parts of stage (2) of this process have been discussed in previous chapters.

Technological influences

A major impetus for the commercialisation of light measurement was the development of reliable physical methods of detection. As discussed earlier, practitioners had, by the 1920s, developed the visual method of measurement considerably, making evident its ultimate reliance on unfatigued and unbiased observers. Such a human-centred technology was not amenable to extensive commercialisation. The advent of reliable phototubes and electrical meters as commercially available components, however, promised improvements of two types: first, lower costs by removing the need for numerous observers, and second, more trustworthy results. This dual advantage led to numerous light-measurement devices for a host of applications discussed below.

The commercialisation of photoelectric light measurement occurred in two distinct stages and exploited two unrelated technologies. Their close association in time suggests the importance of cultural factors in their success. First, detectors relying on the photoelectric effect were refined, particularly at research laboratories such as that of GEC. These devices, incorporating exotic materials in evacuated glass enclosures, supplied with high voltage and monitored by sensitive electrometers (and, later, by galvanometers connected to valve amplifiers) were suitable for some laboratory applications of photometry, but were considered by most to be too fragile for industrial use. Nevertheless, GEC in the U.K. and Westinghouse Electrical & Manufacturing Company in the U.S.A. targeted this market by constructing demonstration devices as diverse as photoelectric smoke recorders, newspaper bundle counters and automatic door openers.[638] By stripping away quantification and retaining merely the ability to *detect* light, these devices found a ready market. Thus,

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[638]See Physical Society and Optical Society, *22nd Annual Exhibition of Scientific Instruments and Apparatus* (London, 1932), 136, and T. M. C. Lance, ‘The electric eye – the photo-electric cell’, in: *The Wonder Book of Electricity* (London, 1932?).

cultural needs translated this delicate and high-precision technology into a reliable and attractive means of automation.

The second, and more financially significant, stage of commercialisation was made with ‘flat plate’ photocells.[639] The first versions of these were simply variants of selenium, which practitioners had used sporadically since the 1880s. These light detectors were relatively inexpensive and imprecise, but small and simple to operate. Quite suddenly, some five years after the commercial introduction of photoelectric tubes, instrument manufacturers began to market portable instruments employing improved variants of the selenium cell. Ironically, these relatively inaccurate sensors proved more successful than their predecessors in bringing quantification to industry.[640] The Weston Electrical Instrument Company in 1932 claimed to have introduced ‘the first commercial dry disc type’ photocell under the trade name *Photronic*, and rapidly marketed a variety of portable meters based on it.[641] Such cells made practicable a variety of products owing to their small size and modest electrical requirements. Other manufacturers responded: Everett Edgcumbe & Co. announced their *Autophotic* plate-type cell a year later.[642] Companies such as Salford

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[639]The financial success is inferred from the number of companies manufacturing or incorporating photocells, rather than phototubes, into products. Much of the commercial importance of phototubes centred not on the measurement of light intensity for scientific purposes, but rather for applications such as sound reproduction in talking pictures and the scanning of photographs for phototelegraphy.

[640]Principally because of simpler electronics and procedures needed to obtain ‘a reading’.

[641]The new cells were publicised in advertisements and in scientific articles which, however, revealed more concerning the cells’ performance than their design. See, for example, B. P. Romain, ‘Notes on the Weston Photronic photoelectric cell’, *Rev. Sci. Instr.* 4 (1933), 83-5, or G. A. Shook and B. J. Scrivener, ‘The Weston Photronic cell in optical measurements’, *Rev. Sci. Instr.* 3 (1932), 553-5. The name *photronic* found brief use as a generic term, thus reinforcing Weston’s claim for uniqueness and helping to consolidate their market. The lack of constructional details, however, increasingly led practitioners to prefer descriptive terms and other manufacturers’ detectors.

[642]E. I. Everett, having served his apprenticeship at the Cambridge Scientific Instrument Co., left in 1884 and founded Everett & Co. twelve years later. In 1898 he was joined by Kenelm Edgcumbe, with the new company specialising in electrical engineering instruments; see Cattermole & Wolfe, *op. cit.*, 23-4. In

Electrical Ltd. used the same idea to produce a variety of instruments for light measurement. Commercial secrecy obscured the technical differences and relative advantages of these devices from the customer.[643] To differentiate their more elaborate and precise – and expensive – products from these flat plate cells, manufacturers of the earlier devices dubbed them *phototubes*. Flat-plate photocells, unlike phototubes, were seldom sold as components because the flat-plate detectors comprised most of the cost of the simple photometers constructed from them. It was in the manufacturers' interest to exploit the technology by selling a complete product, which could have a considerably higher selling price than the detector alone. Moreover, the performance of such devices was not adequate for precise applications such as those performed in photometric laboratories; selling the components on their own would make their limitations more obvious to design engineers attempting to employ them. The commercial success of flat-plate photocells from the early 1930s is attributable as much to marketing as to technological superiority.

The technological benefits of the photoelectric detection of light were publicised on several fronts in Britain: by 1930, members of the NPL photometry department, gradually convinced of the practical superiority of such detectors to the eye, cautiously endorsed their use; their collaborators at the GEC Research Laboratory were demonstrating prototypes of commercial instruments; and, small firms were introducing portable photometers. As noted by one reviewer for *Nature*, 'the introduction of various forms of rectifier photo-electric cell has certainly simplified many problems in the use of instruments such as colorimeters (chemical type), densitometers and the like'.[644] In 1933, the Science Museum recognised this

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1934, the company collaborated with Holophane Ltd to produce 'Autophotometers' employing their Autophotic cells.

[643]Besides the 'photronic' design, newly-marketed photovoltaic and photoconductive materials for cells in the early 1930s included cuprous oxide and lead sulphide. The photovoltaic cells generally comprised a metal disc coated on one side with selenium or cuprous oxide whose surface was covered in turn by transparent layers of metal and protected by lacquer.

[644]Anon., 'Clarity tester for gelatine', *Nature* 137 (1936), 861.

technical and commercial wave by mounting a three-month exhibition of photo-electric equipment.[645]

Relationships between communities

Who were the groups responsible for supporting this commercial growth of light measurement? The links between the communities of designers, producers and users of commercial light-measuring instruments were closely intermeshed, particularly in the early years. These communities interacted in ways that have received relatively little attention in the historiography of instruments or of modern science. While connecting a scientific revolution with the availability of commercial instruments, Baird does not clearly indicate how such inter-dependency operated. Similarly, Rabkin scarcely touches on the subject when he writes:

> The advent of serial, mass-produced scientific instrumentation increased the ease of exploitation. This led to certain alienation of the scientist from the actual design of the instrument, particularly in the 20th century. . . . However, even in earlier centuries the production of instruments, mainly for astronomy and physics, was often affected by non-researchers, popularizers of science or instrument collectors. This phenomenon may not be quite so recent.[646]

Historians have broached the subject of the interaction of different communities, however, for other forms of instrument developed almost contemporaneously with photometers. Christine Blondel, for example, discussing the adoption of the D'Arsonval galvanometer in the latter decades of the nineteenth century, writes:

> At the beginning of the 1880s the scientific and technical territory of industrial electricity is not yet defined. There results, in fact, three intermingled paths, each making its interests felt: that of the inventor, the man of machines; that of the savant, man of the laboratory; and finally that of the manufacturer, subjected to the market and to competition, and who left his name only on the plates of his apparatus.[647]

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[645]Anon., 'Exhibition of photo-electric equipment', *Illum. Eng.* 26 (1933), 97. This included displays of the major types of photocell and their principles, and industrial examples such as package counters, burglar alarms, street lamp switching and daylight brightness meters.

[646]Rabkin, *op. cit.*, 59.

[647]C. Blondel, 'Entre l'électrophysiologie et l'éléctricité industrielle: le galvanomètre à cadre mobile', in: C. Blondel, F. Parot, A. Turner and M. Williams (eds.), *Studies in the History of Scientific Instruments* (London, 1989), 179-91 (my translation).

Brian Gee has also explored the relationship between the scientific research worker and the instrument manufacturer, seeing it, however, as fixed and determined by separate career paths: ‘instrument makers descend from and are tied to their trade in the practical arts by the genealogy of master and apprentice’.[648]

In the case of photometry, and perhaps generally for peripheral sciences like it, the relationship was instead a complex and changing one. The design and production of light-measuring instruments did not involve simply a one-way wresting of control from the hands of scientists to manufacturers. At least four types of relationship between the designer, the manufacturer and the user can be discerned:

(i) a scientific instrument maker constructing custom-made apparatus according to the user’s specification;

(ii) an instrument company manufacturing apparatus developed by or for one user or community of users but made available to other practitioners;

(iii) a company marketing a device originally developed for its own use;

(iv) a firm developing and manufacturing equipment specifically for a perceived market.

Although there was a gradual development from relationships (i) to (iv), examples of each type can be found over the period covered, and indeed up to the present day.[649] Moreover, the definition of the terms ‘manufacturer’, ‘designer’ and ‘user’ varied in each case, although stabilising considerably in the decade before the Second World War. Each term could refer, in specific instances, to a scientist, engineer, industrialist or lay-person, this interchangeability of commercial roles indicating from another perspective the seamless structure of the subject of light measurement. Some brief examples will illustrate the taxonomy of commercial relationships and introduce the firms active in the field.

[648] B. Gee, ‘On attending to the instrument maker in physics history’, in: J. Roche, ed., *Physicists Look Back* (Bristol, 1990), 205-25; quotation p. 217.

[649] Mari Williams, in case studies of early twentieth century instrumentation firms, has noted that no simple pattern of commercial innovation can be discerned. See Williams, *op. cit.*[26] and ‘Technical innovation: examples from the scientific instrument industry’, in: J. Liebenau, *The Challenge of New Technology: Innovation in British Business Since 1850* (Aldershot, 1988).

i) custom manufacturing

In Britain, scientific instrument makers had a long history of custom-manufacturing devices based on the designs of scientists.[650] These instrument makers employed the technologies of their day, and mastered new technologies as they arose. Following this tradition, some produced photometric apparatus. Among the earliest commissions of the Cambridge Scientific Instrument Co., for example, were 'colour mixers' and photographic light meters for William Abney.[651]

ii) manufacturing designs in collaboration with designers

Popular photometer designs could be licensed by the original scientist-designer for sale to others, thus converting him from customer to profit-sharer, when instrument manufacturers perceived a wider market for a custom-made device. The arrival of gas regulation in the 1860s provided just such a market: the firm of William Sugg & Co. manufactured photometers initially for the Metropolitan Board of Works, and the Harcourt pentane standard lamp was designed by one of the Gas Referees.[652] This apparatus was subsequently sold in a variety of forms to gas supply companies, the Board of Trade, and for export to customers as far afield as the Canadian government.[653]

By the turn of the century, the manufacture of licensed photometric apparatus was an active, if limited, business. In collaboration with the PTR in Germany, for example, Schmidt & Haensch manufactured the highly successful Lummer-Brodhun photometer from 1892; Foote, Pierson & Co. of New York manufactured the Ulbricht

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[650] For the instrument-making trade prior to the nineteenth century, see M. Daumas, *Les Instruments Scientifiques aux XVII^e^ et XVIII^e^ Siècles* (Paris, 1953). For surveys of products and manufacturers of the following century, see G. L'E. Turner, *Nineteenth Century Scientific Instruments* (London, 1983); P. R. Clerq, ed., *Nineteenth Century Scientific Instruments and Their Makers* (Amsterdam, 1985); and J. Payen, 'Les constructeurs d'instruments scientifiques en France au XIX^e^ siècle', *Arch. Int. Hist. Sci.* 36 (1986), 84-161.

[651] M. J. G. Cattermole & A. F. Wolfe, *Horace Darwin's Shop: a History of the Cambridge Scientific Instrument Company 1878 to 1968* (Bristol, 1987).

[652] W. J. Dibdin, *op. cit.*

[653] *Ibid.*, 30.

sphere integrating photometer under licence from its German designer; and Kipp & Zonen in Holland manufactured photoelectric microphotometers and galvanometers according to the designs of W. J. H. Moll. In Britain, Alexander Wright & Co. manufactured photometric benches of a type originally supplied for the NPL, and themselves based on PTR models. They also supplied standard Harcourt pentane lamps which the NPL and British industry had adopted as an intensity standard, and even carried out the chemical refining necessary for the purified pentane itself.[654]

Commercial adaptation generally began by seeking new *markets* for an existing design, rather than by modifying the design itself. Thus a 'lustre meter' designed for the Linen Industry Research Association was later marketed unchanged by the Cambridge Instrument Co. to measure the surface gloss of any surface.[655] In the more complex or potentially more versatile designs, however, the manufacturer re-engineered the instrument for commercial production and new applications. The GE recording spectrophotometer of 1935, for example, was the commercial successor to prototypes constructed by A. C. Hardy of the Massachusetts Institute of

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[654] J. Abady, *op. cit.* lists Alexander Wright & Co. as being able to furnish 'all the apparatus for testing gas and materials used in gas works'.

[655] Anon., *J. Sci. Instr.* 8 (1931), 356-8. The company, founded in 1881, was the source of new instrument companies as well as instruments. Some of its former apprentices and managers formed W. G. Pye & Co. (1895), Everett & Co. (1896), the Foster Instrument Co. (1910) and Unicam Instruments (1934). See Cattermole & Wolfe, *op. cit.*

Technology from the late 1920s.[656] Contemporary publications document well the history of this product, indicating its unique status and enthusiastic reception.[657]

Collaborations between the scientist-inventor and instrument manufacturer could benefit both, since the scientist obtained wide recognition for the design, the manufacturer extended his product range and markets, and both generally made money. The association with a prominent scientist could confer status as well as improved sales on the manufacturer. Just as importantly, recognition as a designer could be as important as conventional scientific publications in raising the esteem of some scientists. Both W. J. Moll and A. C. Hardy, for example, were widely acclaimed by their peers as both innovators in instrumentation and as research scientists, roles that they cultivated by publishing several papers on their instrument designs.[658]

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[656]Hardy, professor of Optics and Photography at MIT, was prominent in the field of colour research and spectrophotometry from the 1920s to fifties. He was a key member of the Colorimetry Committee of the Optical Society of America which debated the nature of colour in the 1930s, as discussed in the previous chapter. His recording spectrophotometer and subsequent *Handbook of Colorimetry* have been cited as playing ‘pre-eminent roles in establishing the industrial use of colorimetry’ [D. L. MacAdam, ‘The Hardy recording spectrophotometer and the *MIT Handbook of Colorimetry*’, in: *Golden Jubilee of Colour in the CIE* (Bradford, 1981), 19-22]. The voluminous data of the Handbook, like the earlier stellar magnitude catalogues of Pickering, persuaded practitioners of the reliability and applicability of the new method.

[657]See A. C. Hardy, ‘History of the design of the recording spectrophotometer’, *JOSA* 28 (1938), 360-4; J. L. Michaelson, ‘Construction of the General Electric recording spectrophotometer’, *JOSA* 28 (1938), 365-71; and K. S. Gibson and H. J. Keegan, ‘Calibration and operation of the General Electric recording spectrophotometer of the National Bureau of Standards’, *JOSA* 28 (1938), 372-85. This instrument was quickly followed by other commercial efforts, including a compact instrument designed by the spectroscopist R. W. Wood for the Coleman Electric Company, and instruments by Beckman Ltd. and Adam Hilger & Co.

[658]E.g. W. J. H. Moll, ‘A new registering microphotometer’, *Proc. Phys. Soc.* 33 (1921), 207-16; W. J. H. Moll and H. C. Burger, ‘Set of instruments for measuring spectral absorption’, *J. Sci. Instr.* 12 (1935) 148-52; A. C. Hardy, ‘A recording photoelectric color analyser’, *JOSA & RSI* 18, (1929), 96-117.

iii) commercialisation of an in-house development

Other products were brought out by companies that had developed them for internal use. An example of this form of commercialisation is the Kodak Research Laboratory photoelectric colorimeter, developed to evaluate the characteristics of colour films.[659] The device proved useful to film processors and users as well as to manufacturers. This form of commercialisation was restrained, though, for at least two reasons: manufacturers had little incentive to make available apparatus that could benefit their competitors, and such apparatus usually fell outside the product lines of the company.

iv) manufacturing for a perceived market

In the last decades of the nineteenth century, when enthusiastic amateurs still were able to make significant contributions, some devices were designed and then directly marketed by their inventors. The 'Tintometer' of Joseph Lovibond is an example of one such device that has seen continuous development for nearly a century.[660] A similar case is the colour books and instruments arising from the Munsell colour system.[661]

The successful products of such lone inventors formed the basis of small firms. More frequently, however, an existing manufacturer developed light-measurement apparatus when it had mastered a technology and perceived a commercial need. A particularly early example of this is the Siemens & Halske selenium photometer introduced in 1875. The Hefner lamp was developed by the same company (and had been preceded by earlier, less successful light sources) as a proposed standard for German photometry. Photometric products were a small but nurtured sideline for this dominant electrotechnical company.

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[659]Anon., *J. Sci. Instr.* 10 (1933), 116-8.

[660]The Tintometer Co., founded in 1884, continues to sell photoelectric colorimeters in 1994.

[661]Upon the death of Albert Munsell in 1918, his son and wife extended the products of the Munsell Color Company to include a range of educational and measuring materials.

Extension of commercial expertise

As in the national laboratories before the war, two technological traditions became involved in commercial light measurement in the twenties. The first was supported by optical instrument companies that previously had produced spectrometers and visual photometers, and the second by companies with expertise in electrical instrumentation.

i) photometry via optics

In Britain, several optical firms entered the field of light measurement. Most of these came to manufacture photoelectric devices after having previously marketed versions relying on either visual or photographic technology. Adam Hilger & Co., for example, 'manufacturers of scientific instruments adapted chiefly for astronomy, mathematics and optics' since 1875, was producing microphotometers by 1906.[662] As discussed in Chapter 6, these devices were designed to measure the optical density of spectrographic plates.[663] The photographic recording of spectra was now a routine operation in a variety of laboratory contexts, but practitioners required a means of reducing the data to a graph for quantitative analysis or for publication. Scanning photometers of a variety of designs – nearly all for photographic use – were offered by Kipp & Zonen, Cambridge Instruments Ltd, C. F. Casella & Co. and Holophane, among others.[664] Some optical designs were manufactured long after more precise alternatives were available. Casella, for example, manufactured a visual 'extinction

[662]For more on Hilger, see J. A. Chaldecott, 'Printed ephemera of some 19th-century instrument makers', in: Blondel *et. al.*, *op. cit.*, 159-68; A. F., 'Adam Hilger', *Nature* 56 (1897), 34; and Cattermole & Wolfe, *op. cit.* 141-3.

[663]E.g. Anon., 'Photoelectric absorptiometer', *J. Sci. Instr.* 13 (1936), 268-9, manufactured by Hilger, and F. C. Toy, 'Improved form of photographic density meter', *J. Sci. Instr.* 7 (1930), 253-6. Various terms were used to describe essentially the same device: densitometer, photographic photometer or absorptiometer, with the prefix *micro-* implying an examining region smaller than about one millimetre. For a general discussion of microphotometers, see R. C. Walker and T. M. C. Lance, *Photoelectric Cell Applications* (London, 1933), Chap. 9.

[664]For Casella, see Williams, *op. cit.* [13], 13-14.

meter' for meteorological use until at least 1948.[665] The German optical company Carl Zeiss drew upon its experience as a manufacturer of microscopes and accessories to sell photometers. In a series of advertisements in 1922, they promoted their Pulfrich (visual) photometer for use as a colorimeter, nephelometer, glossimeter and photometer, noting that it 'meets the requirements of the chemical, physiological, textile, paint and other industrial laboratories'.[666]

ii) photometry via electronics

The second technical tradition becoming involved with photometry – that of electrical measurement – was supported by electrical equipment manufacturers.

Weston, an American company, and the British firms Salford Electronics and Edgcumbe & Co., had specialised exclusively in electrical equipment through the 1920s, but photoelectric photometry became a major interest by 1935. Each benefited from prior experience in electrical measurement or from links with other sources of funding or technical expertise. Weston had a long-standing reputation for electrical standards; Salford Electronics was a subsidiary of GEC Ltd.; and Everett, Edgcumbe & Co. had links with photometry through co-founder Kenelm Edgcumbe's membership on the British Illuminating Committee and the Commission Internationale de l'Éclairage.

Among companies from the electrical tradition, the General Electric Company, both in America and England, was the most influential player in the inter-war period. The British version, GEC Ltd., opened research laboratories in 1919, initially concentrating on lighting and photoelectric tubes. The American operations of General Electric Inc. delved into similar areas of measurement, although concentrating on photometric instruments and applications rather than components.[667]

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[665]C. F. Casella & Co., Ltd, 'Gold visibility meter', *Meteorological and Scientific Instruments, Cat. No. 684* (London, 1948), 16. The 'recycling' or retention of outmoded designs to satisfy a conservative market can oppose technological innovation, however. See P. Brenni, 'The illustrated catalogues of scientific instrument makers', in: Blondel *et. al.*, *op. cit.*, 169-78.

[666]Carl Zeiss advertisements in *J. Indus. & Eng. Chem.* 14 (1922), 100, 142, 188.

[667]For histories of GE relating to light measurement, see G. R. Wise, *Willis R. Whitney, General Electric, and the Origins of U.S. Industrial Research* (N. Y.,

New practitioners

Besides the redefinition and consolidation of existing communities of manufacturers and users, commercialisation caused wholly new groups to take up light measurement. These newly involved communities comprised designers, chemists and industrial engineers.

i) instrument designers

The merging of optical and electrical traditions in instrument companies was embodied in individual scientists and engineers, with some designers becoming adept in a new subject that could be termed photoelectric engineering.[668] This demanded an intimate knowledge of both electrical and optical sciences.

New publications in the early thirties signalled the appearance of a self-recognised community of designers. The staff of the GEC Research Laboratory, attempting to convince engineers of the reliability of the photoelectric components that they had developed, and to encourage their use, wrote articles and books aimed at engineers and technically competent practitioners. At least one of these was aimed squarely at the nascent photometric engineering community: *Illuminating Engineering Equipment: Its Theory and Design* promoted the use of photoelectric methods in a new generation of commercial products.[669] Such documentation extended the influence of the instrument makers to a second phalanx of practitioners, loosely binding these peripheral communities which still lacked the unity provided by courses and standards of training.

ii) chemists

Since the late nineteenth century, chemists had accumulated a growing body of knowledge concerning the measurement of chemical concentrations by colour changes. Nevertheless, as late as World War I the term *quantitative chemistry*

1985) and L. S. Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876-1926* (Cambridge, 1985).

[668] As with the study of light measurement itself, the design of instruments did not have a cogent label. Both subjects tended towards conjunctive prefixes such as ‘electro-technical’, ‘opto-electrical’ and ‘electro-optical’.

[669] L. B. W. Jolley, J. M. Waldram and G. H. Wilson (London, 1930), and advertisement, *Illum. Eng.* 23 (1930), 64b.

generally referred to 'wet' techniques such as gravimetric (weighing) and volumetric (measuring) methods.[670] *Indicator* methods relied upon noting the colour change of a

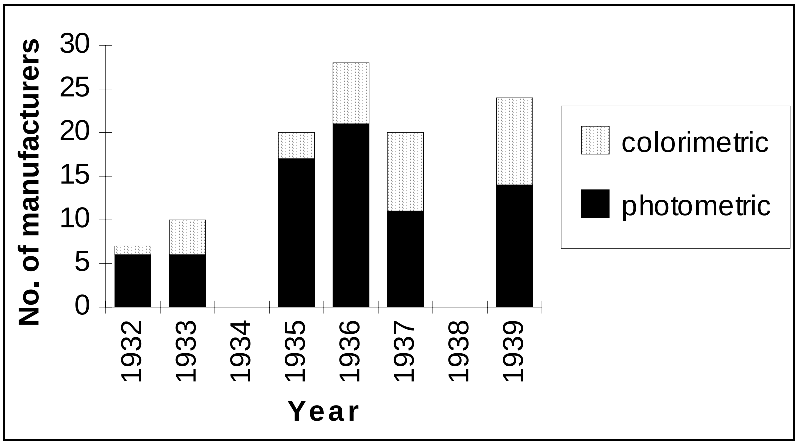

Fig. 20 Commercial light-measuring instruments at the Annual Exhibition of Scientific Instruments and Apparatus, Imperial College, UK. *Source:* exhibition catalogues, 22nd - 23rd, 25th - 27th and 29th Annual Exhibitions.

solution to note a change of acidity, and were inherently non-quantitative.[671] More general quantitative colorimetric analysis demanded standardised methods, and benefited from instruments to ease the task of colour comparison.[672] Unlike photometers, visual colorimeters proved to be technologically undemanding and to have a large market. By 1942 'the number of colorimetric instruments on the market [was] unusually large'.[673] The growth of light-measuring products, and the rising importance of commercial colorimetry relative to photometry, is illustrated in Fig. 20.

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[670]See, for example, F. A. Gooch, *Representative Procedures in Quantitative Chemical Analysis* (New York, 1916), and F. Szabadváry, *History of Analytical Chemistry* (Oxford, 1966).

[671]E. B. R. Prideaux, *The Theory and Use of Indicators* (London, 1917).

[672]See, for example, F. D. Snell, *Colorimetric Analysis* (N.Y., 1922) and N. Strafford, *The Detection and Determination of Small Amounts of Inorganic Substances by Colorimetric Methods* (London, 1933).

[673]T. R. P. Gibb, *Optical Methods of Chemical Analysis* (New York, 1942), xiii.

iii) production engineers

As manufacturers knew well, a convenient method of verifying the uniformity and suitability of many products is to observe their visual appearance. Discoloration of paper, mismatching of fabric colours, and inadequate brightness of electric lamps had all been monitored by human observers by the turn of the century. Such visual verification was awkward to carry out on the industrial scale, as discussed in Chapter 3, and engineers sought means of supplementing or replacing human observers by physical methods. The culture of industrial production could support this transition. Photoelectric measuring instruments may have been accepted in some factories and plants because of the earlier acceptance of cruder photoelectric sensing devices. For the industrial engineer, the knowledge required to operate and maintain a photoelectric paper-bale counter was little different from that needed for a paper-whiteness monitor. The employment of the new technology, and the staff to support it, could be self-perpetuating. By the mid 1930s one engineer reported that such usages were commonplace, and indeed that ‘many miles of street lighting’ were controlled by light-actuated switches, and that ‘most of the large power stations’ employed photoelectric smoke detectors.[674] By stepping back from the problematic physical quantification of light, the crude but simple applications of photoelectric detectors vied with the high-precision applications for the attention of industry

Industrial application of light and colour measurement

The evolution of commercial photometry portrayed above suggests a technology-driven advance. Moreover, the picture presented of commercial development has been one of small firms selling to a diverse but limited range of practitioners of light measurement. The commercial advance of photometry, radiometry and colorimetry was also fueled, however, by genuine industrial needs.

Probably the first major application of light measurement in industry was the measurement of temperature. The first non-contact method to become commercially important was radiation pyrometry. In this technique, a thermocouple or thermopile generates a voltage when illuminated by light from a hot object such as a steel furnace

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[674]C. H. Dobell, *Trans. Illum. Eng. Soc.* 1 (1936), 143.

or pottery kiln. When coupled to a direct-reading indicator or chart recorder, the signal could directly indicate temperature. For materials hot enough to emit visible light instead of radiant heat or 'infrared',[675] the industrial engineer could use optical pyrometry. In this technique the intensity of the sample is equated to that of the filament of a small electric lamp superimposed on the field of view. The current supplying the filament is calibrated in terms of source temperature. An alternative technique was colour-temperature measurement, in which the colour of the glowing body was either compared with a standard by eye or else monitored at two wavelengths by a physical detector. Optical, radiation and colour pyrometers and temperature recorders, researched at the national laboratories before the war, came into common use in chemical plants through the 1920s.[676]

Some manufacturers saw the industrial application of colorimetry for verifying product colours as 'a matter of very great importance'.[677] From its early customers working in academic or government laboratories, the small photometry industry began to turn in the 1920s increasingly towards industrial laboratories and plants. By the 1930s, the measurement of light spanned applications from pure research to quality control in factories. Over 600 American companies manufactured industrial instrumentation, particularly temperature- and pressure-measuring devices. The fraction of instrument sales relative to all machinery increased even during the American depression.[678] Methods that had been used solely in the academic laboratory were applied to industrial problems. Chemists saw spectroscopy, in

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[675]In use by 1880 as 'infra-red' in Britain and by 1920 as 'infrared' in America.

[676]New product announcements and advertisements appeared, for example, in *Chem. Eng. Works Chemist* 'A compact form of optical pyrometer', 12 (1922), 167-8; 14 (1924), 183-4; 14 (1924), 208-9. See also R. B. Sosman, 'New tools for high-temperature research', *J. Indus. & Eng. Chem.* 14 (1922), 1369-74.

[677]H. Barry, 'Investigation of colour problems', *Chem. Age* 18 (1928), 319. For applications, see, for example, C. Z. Draves, 'Color measurements in the dyestuffs industry', *JOSA* 21 (1931), 336-46, and W. B. van Arsdel, 'Color measurement in the paper industry', *JOSA* 21 (1931), 347-57.

[678]From 0.4% in 1919 to 1.4% in 1935. See Bennett, *op. cit.*, 70.

particular, as a new tool for the quantification of mixtures.[679] Transforming the method from a technique used by academic physicists for research in quantum mechanics to the chemist measuring the trace components of steel in a works laboratory demanded standardisation and simplification. Practitioners combined photographic methods of recording with reliable, automated scanning densitometers to yield a viable industrial technique. By 1930, such visible spectroscopy was being supplemented by growing interest in infrared analysis. Chemists at large industrial research laboratories began to adopt infrared spectroscopy in the decade before the Second World War, a trend that accelerated rapidly during the war.[680] University research into the development of visible and infrared recording spectrometers expanded.[681]

Photometry and colorimetry also began to diffuse from the research laboratories to industry. The new availability of what managers regarded as reliable and objective instrumentation led to wide-scale interest in applying quantitative light measurement to industrial problems. All applications calling for the evaluation or

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[679]C. G. Nitchie, 'Quantitative analysis with the spectrograph', *Ind. & Eng. Chem.* 1 (1929), 1-18.

[680]Y. M. Rabkin, 'The adoption of infrared spectroscopy by chemists', *Isis* 78 (1987), 31-54, and S. F. Johnston, *Fourier Transform Infrared: A Constantly Evolving Technology* (Chichester, 1991).

[681]In America, the technique of infrared spectroscopy spread substantially from two centres: the National Bureau of Standards at Washington, D.C., and The Johns Hopkins University some fifty miles away. William Coblentz at the NBS had been measuring infrared absorption spectra of materials since the turn of the century. At Johns Hopkins, the research group of Harrison Randall concentrated on developing instrumentation and extending measurements to ever-longer wavelengths. The group also devoted considerable effort to improving methods of detecting radiation. The thermocouples they used were conceptually the same as those used in the previous century. Randall's group developed schemes for discounting the effects of changing temperature (which caused the thermocouple voltage to drift). This perturbation from outside disturbances was the major limitation in measuring infrared intensity. Just as importantly for acceptance of the techniques, Randall's collaborators developed recording spectrometers. These early systems had to be proven to give results as accurate and repeatable as manual measurements. For an account of this crucial American work, see H. M. Randall, 'Infrared spectroscopy at the University of Michigan', *JOSA* 44 (1954), 97-103. The evolution of infrared radiometry, although related to and paralleling developments in visible light measurement, will not be discussed in detail here.

standardisation of colour were affected. The textile industry, for example, began to employ colorimeters for matching the colours of dyed fabrics,[682] and paint manufacturers tested new formulations and the uniformity of production.[683]

The adoption of light measurement by industry fed back into the technology itself. The requirements of industrial apparatus were different from their laboratory counterparts. For routine applications, equipment had to be robust, simple and reliable. Reliability demanded devices to be insensitive to environmental factors and to be stable over weeks or months. This, in turn, required that the optical detectors, electronic and mechanical components did not degrade with time. Such a goal was impracticable given existing phototube and thermionic valve designs. To overcome hardware limitations, designers used the strategy of correcting for imbalances, drifts and fluctuations. The need for 'self-compensation' of imperfections and the desire for automatic recording were rapidly combined into self-registering photometric instruments almost as soon as photoelectric methods of measurement became available.[684] As John Walsh had predicted, the greater precision of photoelectric photometry also allowed more rapid measurements, opening new directions of research.[685]

Backlash to commercialisation

Portions of the process industry, where analysts were trained, if at all, in more traditional wet chemistry techniques, received light measurement coolly. Indeed, the new photometric and colorimetric instruments appeared almost *too* easy to use by unskilled personnel, endangering existing jobs for chemists at industrial plants. One

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[682] R. D. Nutting, 'The detection of small color differences in dyed textiles', *JOSA* 24 (1934), 135.

[683] F. Benford, 'A reflectometer for all types of surfaces', *JOSA* 24 (1934), 165.

[684] For example, H. M. Randall and J. Strong, 'A self recording spectrometer', *Rev. Sci. Inst.* 2 (1931), 585-99, and F. S. Brackett and E. D. McAlister, 'The automatic recording of the infrared at high resolution', *Rev. Sci. Instr.* 1 (1930), 181.

[685] One new direction was the study of very short time scales in photometry made possible by the rapid response of phototubes. See, for example, L. H. McDermott and F. W. Cuckow, 'The time lag in the attainment of constant luminous output from tungsten filament electric lamps', *J. Sci. Instr.* 12 (1935), 323-7.

trade editorialist felt it necessary to calm concern by emphasising the skill needed for photometric techniques:

> It may be mentioned that the fear of certain chemists that the introduction of a spectrograph into their laboratories might tend to prejudice their position and prospects is entirely without foundation. It is obvious that only a worker trained in the use and theory of scientific instruments could hope to control successfully the more delicate operations involved, and while unskilled workers can, and do, operate a kind of spectroscope in the sorting sheds of many steel works, it needs scientific training of no mean order to operate a logarithmic wedge sector and interpret the results correctly.[686]

While rejecting the idea that chemists should have to behave like physicists, the editorial called for both elementary and advanced training in optical methods for industrial application, noting that 'when the importance of applied optics generally is remembered, it is a matter of surprise that such has not already been done'.[687]

The conservatism of users and their lack of training for industrial application of the techniques were not the only difficulties, because the ease of use was deceptive. Commercial light measurement proved to have associated technical problems. The instrument firms had marketed automated photometry and colorimetry as a straightforward method of increasing efficiency and reducing overheads in industrial applications. Like the scientists in the standards laboratories, however, workers in industry began to recognise unanticipated complexities in the new techniques.

Quantification did not always provide solutions. Discussing the automatic detection and recording of smoke levels from factories, one engineer noted:

> it is often considered – and with justification – that a qualitative record which merely shows "smoke" or "no smoke" is preferable to the quantitative record which indicates degrees of smoke density. Not only is it difficult to establish a calibration for all thicknesses of smoke strata, but any such device which is operated by the valve anode current depends for its accuracy on the constancy of that current which cannot be guaranteed throughout the whole of its working life.[688]

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[686]For a detailed description of the use of log-sector discs for determining the intensities of spectral lines (and thereby quantifying chemical constituents), see Gibb, *op. cit.,* 49-52.

[687]Anon., 'Industrial spectrum analysis', *Chem. Age* 33 (1935), 1.

[688]Walker, *op. cit.,* 132-3.

Moreover, physical photometers, like the eye, were subject to errors that were not always obvious. One designer, observing that 'photo-electric cells are good when used very cautiously, but are apt to lie "without blushing"', vaunted the more faithful spectral, angular and linear characteristics of his device.[689] The complexities of photoelectric devices were as mistrusted as visual methods had been three decades earlier.

The quantification offered by the manufacturers was increasingly seen as incomplete or misleading. As discussed in Chapter 7, research into light and colour, particularly when related to real industrial situations, had enlarged the number of visual characteristics to be quantified. Besides the hue, saturation and brilliance of coloured light, the surfaces of real materials had optical attributes such as lustre, sparkle, luminosity and gloss. Discussing these problems, the chairman of the American Committee on Colorimetry wrote:

> [The modes of colour] are strictly phenomenal or experiential attributes, not reducible to physical terms, and demonstrable only by introspection. However. . . the conditions for their presence in consciousness can be specified objectively, if we assume the response system to be normal in its other stages.[690]

Separating the subjective and physical characteristics of light and colour was no longer just a problem for scientific committees: it was being faced daily and directly on the factory floor. Writing of his mixed experiences with colorimetric instruments, a representative of the Printing and Allied Trades Research Association (London) observed:

> Unfortunately, the spectrophotometer is a costly instrument and requires skilled operation: as a result, many so-called reflectometers, whiteness- and brightness-meters have made their appearance. In the commonest of these, light from the sample is received by a photocell, and readings are taken with red, green and blue filters in front of the cell; such instruments are inexpensive and simple to operate. It is not generally realised, however, that papers are not necessarily a good match even when the 'red', 'green' and 'blue' readings are the same; conversely, papers may be a good visual match and yet give different readings. . . it is not commonly appreciated in the trade

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[689]S. English, 'Some properties of the cells used in Holophane-Edgcumbe Autophotometers', *Illum. Eng.* 28 (1935), 94-6.

[690]L. T. Troland, *Psychophysiology* (New York, 1929), Vol. 1, 254.

> that colour is 'three-dimensional', and that consequently no single instrument reading can define a colour.[691]

Contrasting earlier pronouncements, even the head of Colorimetry at the NBS cautioned that physical methods were not a panacea:

> in spite of claims made by manufacturers and others using photo-electric cells the eye is often a better instrument than the photo-electric cell. . . For certain portions of the spectrum they are much better than the eye, but in others, and in many problems in photometry, the chief advantage is speed.[692]

The measurement of light and colour was proving to be unexpectedly recalcitrant in converging towards a technological solution. Colour was a subjective sensation difficult to quantify and accord between different observers, let alone 'physical' instruments. The 1931 CIE specification of the 'standard observer' made possible the numerical expression of colours, but did not make colour matching any easier. Nor did it deal with the properties of surfaces. Two options were available: either to use human observers and visual photometers – i.e. to revert to conventional but tedious colour matching – or to employ physical photometers. The adoption of physical instruments could assure more repeatable measurements, but at the expense of generality: their numbers were not necessarily related closely to the visual perception of appearance. The demand for rapid and reliable testing of products during the thirties argued for physical methods, just as the testing of incandescent electric lamps had done in the national laboratories a decade earlier. Again, practitioners made the shift from physiological to physical methods. Their pragmatic solution was the development of specialised instruments to measure more of the awkward visual characteristics.

New instruments and new measurements

The discussion of new communities of practitioners and technologies must proceed in parallel with that of new types of measurement. The new communities, in some cases, attempted new forms of quantitative light measurement, to which the firms in light measurement responded by selling instruments. In other cases, new

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[691] V. G. W. Harrison, 'Physics in the printing and paper-making industries', *J. Sci. Instr.* 18 (1941), 103-9.

[692] K. Gibson, 'Progress in illumination', *Illum. Eng.* 21 (1930), 265-272; quotation p. 271.

technology made possible a measurement that proved widely useful to practitioners. The spectrometer manufacturer, Hilger, exemplified the latter case, publicised the technique of absorption spectrophotometry by publishing bibliographies of papers on the subject.[693]

Photoelectric technology made practicable a variety of measurements that had previously been laborious or inaccurate. The measurement process, though, had to be diversified. With a carefully designed instrument, the reflection of light from surfaces could now straightforwardly be quantified.[694] For surfaces that did not have a mirror finish, the surface texture caused light scattering. ‘Gloss’, this diffuse/shiny characteristic of surfaces, was important in the porcelain, cloth, ceramic, and metals industries, and was measured by an instrument bearing the ungainly name *roughometer* in America and *glossmeter* in Britain.[695]

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[693]O. J. Walker, *Recent Applications of Absorption Spectrophotometry* (London, 1932), and *Absorption Spectrophotometry and its Applications: Bibliography and Abstracts 1932 to 1938* (London, 1939).

[694]L. Bergmann, ‘A practical photoelectric reflection meter’, *Zeit. f. tech. Physik* 14 (1933), 157-8.

[695]Salford Instruments Ltd, ‘Comparative gloss meter’, *J. Sci. Instr.* 14 (1937), 32-3. Other alternatives were *glossimeter* or *reflectometer*.

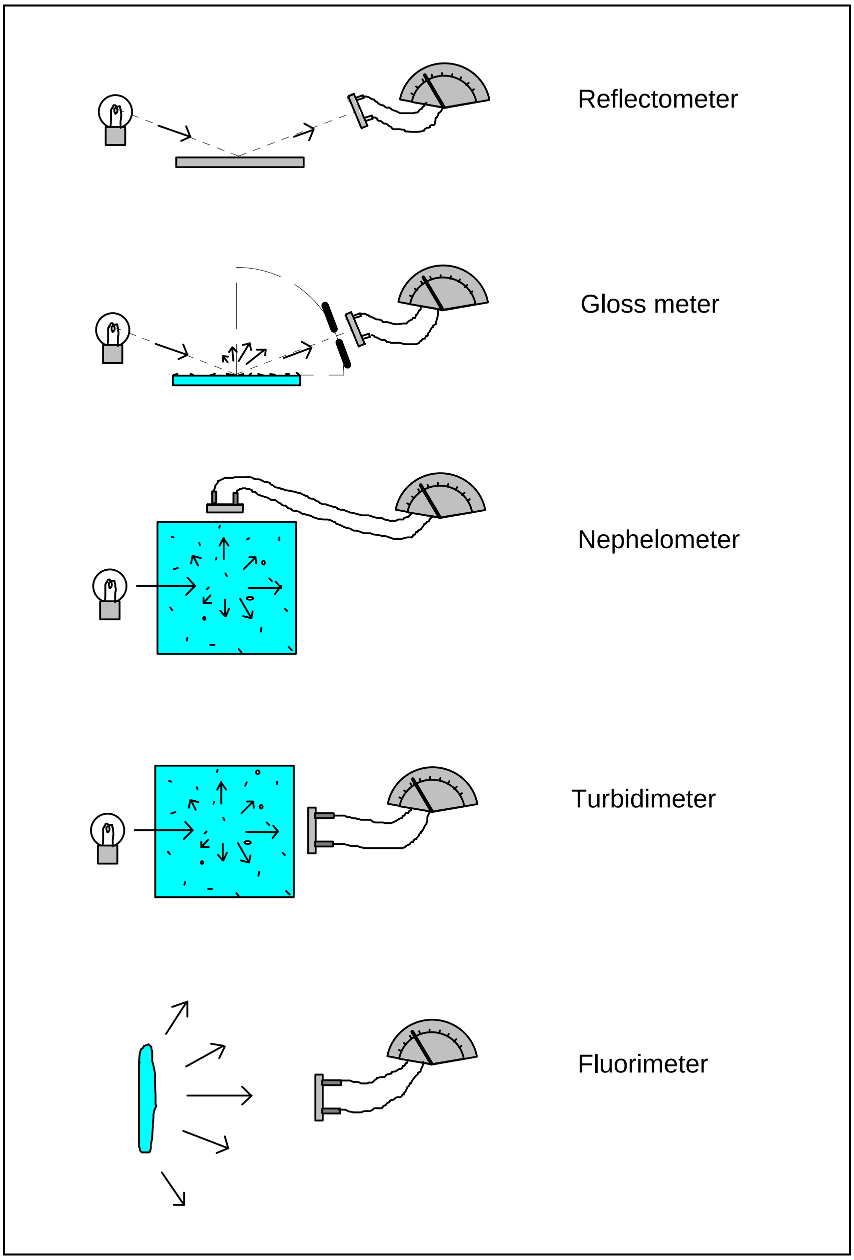

Fig. 21 New types of photometric instrument commercialised in the inter-war period. Rearrangements of light source, sample, photocell, wires and meter generated new forms of measurement.

From the early 1930s, Adam Hilger & Co. manufactured the *blancometer*, a photoelectric instrument design to match nearly white surfaces of similar texture.[696] In it, light was reflected from an incandescent source into a photocell, alternately from a white magnesium oxide reference or from the sample under investigation. Adjustable wedges of graded transparency could be positioned to yield the same

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[696] Anon., 'New instruments', *J. Sci. Instr.* 11 (1934), 62.

reading from both materials on an electrometer connected to the photocell. To determine the colour of the sample surface, coloured filters could be interposed in the light path to pass red, green and blue light. In another instrument, turbidity, a measure of the light transmitted by a liquid or gas containing particles, was employed to infer the size of dust particles.[697] The same principle was used in the closely related *nephelometer*, which measured the light *scattered* from liquids containing particles. This version proved popular in measuring the purity of water supplies. Other characteristics that had previously been estimated by eye gained dedicated photoelectric instrumentation, e.g. *fluorimeters* to measure the fluorescence from materials[698] and *polarimeters* to measure the polarisation of light reflected from surfaces.

For most users, though, photoelectric methods remained a two-step process. The majority still employed photometric instruments principally for measuring the density of photographic plates. Scanning photometers for analysing photographically recorded spectra were the most common type of instrument developed in the decade before the war.[699]

Photometry for the millions

Spencer Weart has observed that ‘the 1920s were a golden age of scientific faith, not only among scientists and industrialists but also for the public at large’.[700] The public, while able to marvel at the demonstrations of photoelectric devices, could not participate in this aspect of the golden age until inexpensive and simple devices

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[697]E. G. Richardson, ‘A photo-electric apparatus for delineating the size-frequency curve of clays or dusts’, *J. Sci. Instr.* 13 (1936), 229-33. The technique came to the attention of many chemists through the paper by R. C. Tolman, L. H. Reyerson, E. B. Vliet, R. H. Gerke and A. P. Brooke, ‘The relation between the intensity of Tyndall beam and concentration of suspensions and smokes’, *J. Am. Chem. Soc.* 41 (1919), 300-3, which coined alternate term *tyndallmeter*.

[698]The fluorescence from radium intended for instrument dials had been the subject of an investigation at the NPL during WWI, and employed visual methods.

[699]E.g. J. H. Lees, ‘A recording microphotometer’, *J. Sci. Instr.* 8 (1931), 272-9 and Lance, *op. cit.* [42], 45-54.

[700]S. R. Weart, ‘The rise of ‘prostituted’ physics’, *Nature* 262 (1976), 13-7; quotation p. 14.

became available.[701] Moreover, the entities measured had little relevance for the general public. But the disc-type photocells introduced in the early thirties caused photoelectric technology to diffuse widely, multiplying the number of devices and users. Two products based on disc-type photocells proved immediately popular, and were produced in numerous variants: *illumination meters*, used to measure the lighting level in buildings or on streets, and *exposure meters* for photography. Illumination meters were frequently calibrated in terms of the 'daylight factor', i.e. the fraction of illumination compared to unobstructed daylight.[702] Holophane, a major supplier of prismatic light fittings, also became the chief British source for light measuring instruments in the 1920s. In 1930 the company introduced a 'sill ratio meter' specifically to measure the daylight factor. Their promotional literature emphasised the legal importance of such a measurement, noting that the Prescription act of 1832 endowed windows that had enjoyed free access of light uninterruptedly for twenty years with certain rights of light. Since 1865 'attempts have been made . . . to consider the questions involved in such cases in a quantitative manner'. Holophane's solution was to compare the intensity of a uniformly bright or dull sky with that of the room by means of a sill-mounted visual photometer.[703]

As discussed in Chapter 2, early photographers had made little use of light measurement devices. Commercial 'exposure meters' had not had much success until the end of the 1870s, when gelatine plates manufactured with a predictable and sensitive response to light became widely available. A number of exposure devices appeared on the market after that time, relying on a variety of technologies.[704] The

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[701]E.g. Lance, *op. cit.* [17].

[702]E.g. G. P. Barnard, 'Portable photoelectric daylight factor meter', *J. Sci. Instr.* 3 (1936), 392-403. The 'daylight factor' had been suggested by Alexander Trotter in 1895, and popularised by the NPL/DSIR studies by P. J. Waldram of building illumination from 1923. Room illumination 1% as bright as outdoors was deemed good, but < 0.4% poor.

[703]Anon., 'The Holophane sill-ratio meter', *Illum. Eng.* 23 (1930), 278.

[704]The devices in one collection have been classified by their curator as either (i) exposure tables or calculators; (ii) tintometers, relying on the darkening of a standard photographic paper; (iii) extinction meters, employing apertures or absorbing filters to restrict the light reaching the eye to the threshold of detection,

range of commercial exposure devices remained broad but static until the early 1930s, when the photoelectric version first became available.[705] Physical light measurement entered the popular domain with the electrical ‘exposure meter’ having a dial calibrated in terms of film sensitivity and camera apertures for amateur and professional photography.[706] While ‘faster’ photographic emulsions were then appearing, the success of such devices probably owes as much to consumer fashion as to technical benefit.

By the mid 1930s, simple physical photometers of this type were popular among engineers and photographers alike. A Swiss lighting engineer commented:

> The development of the inexpensive, fairly reliable and fairly accurate photovoltaic cell photometer was itself an item of major importance to the development of better lighting. For the first time, the travelling agent, the consulting engineer, the student of lighting, every person interested in establishing a record of an intensity of lighting was given the means to do so. The instrument is so much simpler than those previously used that these have been completely superseded for demonstration purposes.[707]

Nor were photoelectric detectors confined solely to photometry. Many practising engineers found that ‘the simplest applications of photocells are frequently the most useful ones’.[708] Inventors realised that the simple photocell could be integrated into

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or (iv) photoelectric meters. See D. B. Thomas, *The Science Museum Photography Collection* (London, 1969), 37-44.

[705]One of the first of these was the Weston 617 Universal Exposure Meter of 1931, which combined two selenium cells and a micro-ammeter. [D. B. Thomas, *Science Museum Photography Collection* (London, 1969), cat. no. 271] and Physical Society and Optical Society *25th Annual Exhibition of Scientific Instruments and Apparatus* (London, 1935).

[706]For contemporary descriptions of the new technology, see G. B. Harrison, ‘Photoelectric exposure meters’, *Photog. J.* 74 (1934), 169-77, and E. Nähring, ‘Photoelectric exposure meters’, *Photog. Indus.* 36 (1938), 1358-62 and 1384-86.

[707]C. A. Atherton, Comité d’études sur la pratique de l’éclairage, *Compte Rendu CIE* (London, 1935), 653.

[708]R. C. Walker, ‘Some applications of light-sensitive cells’, *Trans. Illum. Eng. Soc.* 1 (1936), 129-34; quotation p. 132.

ever more complex products produced in larger volume and with higher profit. Even Albert Einstein co-patented an automatic exposure system for a camera.[709]

A better image through advertising

The advertisement of commercial light-measuring products had a significant influence on the status of the technology and its perception by the scientific and engineering communities. At the close of World War I, photometry was relatively stagnant; publications had fallen, and visual observing techniques had been taken close to their practical limits.[710] The introduction of photoelectric technology to a wider community in the early 1920s was initially slow, as it appeared unreliable and complex. Advertising and commercial demonstrations transformed the image of this faltering subject, however, into one of modernity and control. Indeed, as Brian Gee has noted, for both contemporary scientists and historians 'the first appearance of an item in a trade catalogue often signals that research and development [has] reached the point of commercial viability'.[711]

The earliest print advertisements simply publicised the availability of a type of apparatus, and appeared in trade journals. Established firms such as The Tintometer Co. and Hilger & Co., for example, advertised in *The Journal of Scientific*

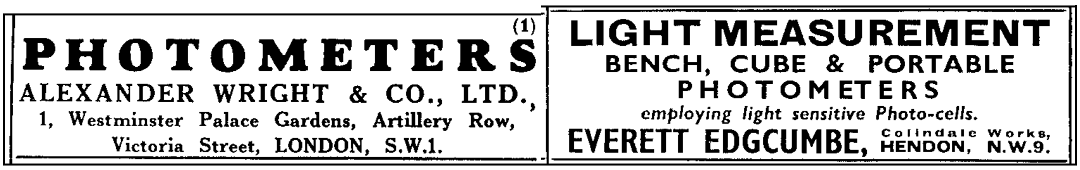

Fig. 22 Photometer advertisements, *Illum. Eng.* 26 (1933), 56 and 28 (1935), 30.

Instruments. Advertisements for photometers by Alexander Wright & Son and Holophane appeared in *The Illuminating Engineer*. As competition for customers

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[709]Einstein and Gustav Bucky, a radiologist, obtained U.S. patent 2,058,562 in May, 1936 [Abraham Pais, '*Subtle is the Lord. . .': The Science and Life of Albert Einstein* (London, 1982), 495]. A cine camera marketed in Austria in 1935, the Eumig C-2, was the first to incorporate a photoelectric meter coupled to a lens aperture. Kodak sold a still-camera version from 1937 for the luxury market.

[710]Appendix III plots publications in photometry for the early twentieth century.

[711]Gee, *op. cit.*, 223.

rose and new customers unfamiliar with the technology sought instruments, however, advertisements assumed a more didactic and propagandistic theme.[712] Ready-made apparatus for the neophyte began to appear. The Holophane company presented the *Lumeter* as the solution to the problem of measurement of the illumination from light sources, although no description was given of its principle of operation or method of use.[713] Instead, advertisements curtly provided the company address, the product name, and a brief description of the size, weight and intended use of the instrument.[714] Such advertising strategies not only literally 'black-boxed' the instrument, but attempted to 'black-box' the not inconsiderable operating complexity as well. Through the 1920s, the Lumeter was the only regularly advertised photometer in Britain. Its commercial success in a changing market is implied by frequent design updates. Such remodelling of designs was novel in a field that only a few years earlier had been commercially dormant, and soon caused it to rival the automotive industry in innovation. An advertisement claiming the Lumeter to be 'entirely redesigned, and a number of improvements made',[715] was followed a few months later by another announcing that 'the 1926 Model is now available conforming with all requirements of the new British Engineering Standards Association Specification No. 230, 1925'.[716] By 1930, however, advertisements began to coax purchasers by the threat of legal impositions: 'To test street lighting for conformity with the British Standard Specification use the Holophane Lumeter'.[717] Despite its commercial dominance the Lumeter, based on the visual comparison of an internally and

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[712]A similar observation has been made about other types of industrial instrument in the inter-war period: 'Companies saw themselves as consultants and educators as well as suppliers of instruments' [Bennett, *op. cit.*, 72].

[713]The first version of the Lumeter was invented by J. S. Dow (a long-time officer of the Illuminating Engineering Society of London) and V. H. MacKinney in 1910. See J. W. T. Walsh, 'The early years of illuminating engineering in Great Britain', *Trans. Illum. Eng. Soc.* 16 (1951), 49-60.

[714]E.g. Holophane Ltd., 'The Holophane Lumeter', *Illum. Eng.* 22 (1929), 156.

[715]Holophane Ltd., 'The Holophane Lumeter', *Illum. Eng.* 19 (1926), 30.

[716]Holophane Ltd., *Illum. Eng.* 19 (1926), 804.

[717]Holophane Ltd., *Illum. Eng.* 23 (1930), 19.

externally illuminated screen, lost its privileged status the following year when inexpensive photoelectric meters began to appear. These newer devices stressed versatility for a variety of uses. The *Luxometer* of Everett, Edgcumbe & Co., for example, was advertised ‘for measuring candle-power, illumination, surface brightness and daylight factor’, making it capable of performing all the tasks required by practitioners of light measurement.[718]

As quickly as manufacturers marketed the new instruments for physical photometry, their purchasers deployed them to convince the next level of customers of their modern practices. An advertisement by Regants Lamps Ltd., for example, was aimed at optical manufacturers, and emphasised the scientific basis of their own production:

> The Regants glass is the only glass of its kind on the British market. . . come and see it in our laboratory. Test it out on our spectrometer. Get its spectral wave lengths. In your search for the better, GET THE BEST.[719]

The ability to *measure* and *illustrate* the transparency of glass became a selling point. Light measurement was thus being co-opted to demonstrate the quality of other products. A similar theme is apparent in a 1932 advertisement that announced ‘photoelectric cells from the “His Master’s Voice” laboratories for efficiency and reliability’.[720] Such cells had had, even five years earlier, a reputation for precisely the opposite characteristics: irregular performance, poor uniformity and instability.

Demonstrations, more than print, served as a particularly effective advertising medium. General Electric and Westinghouse devoted considerable engineering time to designing demonstration apparatus as well as to publicising their products in advertisements, magazines and books. GEC demonstrated phototube technology with relatively undemanding exhibits. Typically, a beam of light shining on the phototube,

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[718]Everett, Edgcumbe & Co, *Illum. Eng.* 24 (1931), 226a.

[719]Regants Lamp Ltd advertisement, *Illum. Eng.* 22 (1929), 48.

[720]The Gramophone Company, *Physical Society and Optical Society 22nd Annual Exhibition of Scientific Instruments and Apparatus* (London, 1932), iv. Such cells were used in both sound films and experimental television systems from the late 1920s. See, for example, R. W. Burns, ‘The contribution of the Bell Telephone Laboratories to the early development of television’, *Hist. Technol.* 13 (1991), 181-213.

when interrupted, would trip a relay to operate a motor or other device. These so-called ‘electric eyes’ found commercial application in the following decade as automatic door-openers. Other common applications included the

counting of objects on conveyor belts, and the detection of web fractures on paper-making and printing machines.[721] The Osram subsidiary of GEC also used photoelectric cells to advertise its products, producing several demonstration

[721]Walker, *op. cit.*

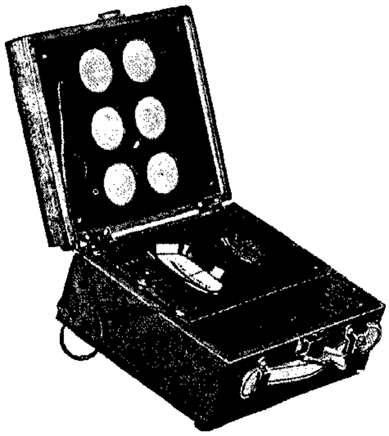

Fig. 23 Weston advertisement, *Illum. Eng.* 28 (1935), 26.

novelties to encourage the use of its cells by other companies.[722] In one such novelty, a customer's hand picking up leaflets from a distribution box interrupted the light beam to ring a bell. In another, the demonstrator could use an electric hand torch to steer a model motor car by directing the beam onto one of two phototubes connected to corresponding thermionic valves and relays controlling a steering motor. These 'magic' demonstrations emphasised the qualities of automated seeing, effortless manipulation and action at a distance. Indeed, 'magic eye' became a popular and enduring euphemism.[723] In this way the phototube's potential for detection and control were brought home to a receptive public. As a direct result of such exhibits and portrayals, the trend to physical photometry grew during the following decade, and was virtually complete by World War II. By 1939, the term *photometer* was almost universally preceded by the adjective *photoelectric* in the titles appearing in instrument journals.[724] Practitioners clearly had come to perceive photoelectric methods as implying stability, accuracy and modernity.

The commercialisation of light measurement – that is, trade in instruments themselves – was thus one of the last and most powerful factors to shape its social presence. This economic dimension, fueled by advances in technology, supported the most rapid evolution that the subject had yet undergone. For the first time, the measurement of light was convincingly portrayed and almost universally perceived as a useful and accurate technique for scientist and layman alike.

Yet the increased public profile and commercial success of light measurement was not solely, or even predominantly, a technology-driven affair. Indeed, the

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[722] R. C. Walker & T. M. C. Lance, *Photoelectric Cell Applications* (London, 1933), 81-3.

[723] E.g. 'Eleven pairs of "magic eyes" have counted approximately 7,000,000 motor vehicles during the last year' [*Baltimore Sun*, 22 Feb 1938, p.20].

[724] A standard for flat-plate photoelectric cells was written during this period: *British Standard Specification for Photo-electric Cells No. 586-1935*. Descriptions deal with properties such as working voltage, colour temperature, ageing process, minimum sensitivity, maximum change of sensitivity, maximum slope, maximum dark current, frequency response and light flux incident on cell.

cultural invention of a *need* – that of industrial matching and testing – predated reliable photoelectric detectors. Nor did the consensus regarding quantification alone impel its acceptance: the first commercial inroads were made by devices that merely *sensed* rather than *measured* light. Other, cultural, factors also played a role, particularly in the placing of an increased value on automation and standardisation. As in the earlier phases of its development, the measurement of light was influenced by a host of inter-relating factors.

Chapter 9
Light Measurement as a 'Peripheral' Science

The quantification of light

The previous chapters have illustrated the gradual and faltering progression towards the quantitative measurement of light and colour. Practitioners of photometry were willing, if late, participants in the general trend towards mathematisation in physical science and engineering. Utilitarian need, principally the regulation and comparison of lighting systems, was the primary incentive for its development. The dilatory transition from qualitative 'notions' to quantitative 'measures' of intensity was due to several causes. The human eye, the sole arbiter of brightness over most of the period, was disappointingly fickle in response; the units of measure were confusing to many practitioners; the contentious 'standards' of intensity could be maintained only to relatively poor tolerances. When practitioners came to replace the eye by seemingly more promising physical detectors – a matter of faith more than substantiated claim – these were found, in turn, to introduce their own complexities in the measurement process. Widespread acceptance of such detectors hinged not on their ability to quantify but rather on their facility to automate.

Colour measurement followed a somewhat different path. Practitioners seeking utilitarian application of colour metrics consciously limited the boundaries of their subject. Replacing the substantial complexities of human colour perception by a nominal 'standard observer', they thereby constructing a framework within which quantitative analysis was possible. Because the approximations inherent in this system introduced problems for applications that demanded a description of more complex colour properties, colour measurement, while widely adopted after the 1931 standardisation, continued to be contentious. The standardisation was unsatisfactory also for psychologists, for whom the utilitarian advantages were of little consequence and avoided the deeper issues of colour perception that they and philosophers wished to address. The quantification of colour, then, was seen by the Second World War as a convenient makeshift. Its rapid promulgation, however, made subsequent modifications to this provisional and incomplete quantitative system difficult.

In what way, then, did the quantification of light and colour succeed between the late nineteenth and early twentieth centuries? The cases examined have argued that it provided, even more than a language of numeracy, a means of standardising discussion. Astronomers could compare observations; inspectors could pass or fail lighting installations; industrialists could match and specify tints. By facilitating such common bases, light measurement promoted scientific communication and unity. On the other hand, the main thrust of the quantitative method – its numerical specification and arithmetic manipulation of intensity values – can be seen as having been less encompassing and fruitful. Practitioners repeatedly voiced concern about the ability and desirability of replacing the unreliable human eye by a physical measurement, and this was paralleled by the discovery of imperfections of the physical methods themselves. Quantification of light proved a technically difficult achievement. Moreover, human vision remained inextricably part of the process of light measurement, whether manifested in a human observer, in a recorder of dial readings or as a disembodied table of average visual response.

Evolution of practice and technique

Moving from the quantitative features of this science-on-the-sidelines, we can sketch the main characteristics of its historical development. The more technical changes in the subject comprised:

(a) the widespread identification of quantification as a desirable goal around the turn of the twentieth century;

(b) the supplanting of visual by physical methods from the late 1920s;

(c) a convergence of the techniques used for measuring light, colour and invisible radiation by the Second World War.

Social and institutional transitions included:

(d) adoption of photometry for illuminating gas inspection *c*1860;

(e) growing interest in electrotechnical uses after 1880, when electric and gas lighting systems began to compete;[725]

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[725]Reflected in the publication rate, as detailed in Appendix I.

(f) rise of the illuminating engineering movement *c*1900, having the standardisation of photometry as a major goal;

(g) research at government laboratories from *c*1900, and at industrial laboratories a decade later;

(h) efforts at regulation and definition of the subject by delegations during the inter-war period;

(i) commercialisation and industrialisation of photoelectric instruments after 1930.

This enumeration highlights the importance of cultural, as well as intellectual, factors in influencing the subject.

Convergence of practice

The evolution of light measurement between the last decades of the nineteenth century and World War II can be viewed as a gradual convergence, selection and stabilisation. There was a *convergence* of ideas regarding how light and colour should be described and treated. From a collection of isolated communities (including astronomers, gas inspectors and photographic researchers), the practitioners moved towards a shared viewpoint favourable to quantification and to the physical methods of measurement that facilitated it. A greater number of scientific communities became familiar with light measurement as the technology developed, and embraced the well-defined objective of the quantitative measurement of light intensity and colour.[726] This trend towards quantification cannot be seen as a natural progression; rather, the desire for measurement is a consequence of particular

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[726]Exceptions to this are few indeed. For light measurement, at least, I have been unable to find any proponents of a non-quantitative treatment of light after WWI. Interest in light measurement was by then restricted to 'scientific' applications (in the broadest sense, and as opposed to metaphysical or artistic appeal) and 'scientific' methods, which by the inter-war period were firmly equated with quantification. On the other hand the subject of colour, engaging the interest of artists and philosophers, was never convincingly constrained by the desire for quantification. Examples of metaphysical and philosophical enlargements of the concept, and influence, of colour include: R. Matthaei and H. Aach (eds.), *Goethe's Colour Theory* (London, 1971); J. Westphal, *Colour: a Philosophical Introduction* (London, 1987) and D. R. Hilbert, *Colour and Perception: a Study in Anthropocentric Realism* (Stanford, 1987). Such dimensions fall outside the scope of this work, which traces the progressive *narrowing* of the notion of colour by scientists to suit their objective of quantification.

cultural goals emphasising the comparison and standardisation of goods and services.[727] The general acceptance of quantification implicitly involved *selection* of concepts deemed important. Thus the assurance of uniform manufactured goods and demonstrably adequate lighting was generally perceived as being more worthy of attention than, for example, poetic or aesthetic descriptions of light and colour.[728] Such standards *stabilised* the subject and aided consensus.

A second factor in the convergence of practice was the underpinning of the new conceptual objectives by technological advance. Investigation of the photoelectric effect allowed the realisation of physical photometry. Practitioners deemed the modelling and ultimate replacement of human visual characteristics by physical analogues – even averaged and highly simplified models – as important in enabling applications of light and colour measurement. Hence the ready acceptance that the photocurrent produced by illuminating a phototube was a measure much like human vision – even a superior measure, in that it was unaffected by other human characteristics such as fatigue. The consensus of the practitioners in all communities on this point is indicated by the rapid transition from visual to photoelectric methods, which occupied a period of scarcely fifteen years. Within a portion of the career of a practising scientist or engineer, then, the measurement of light was transformed from a human-centred to an instrument-centred activity.

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[727]On the cultural motives for quantification, and its limited penetration into everyday life, see J. Lave, ‘The values of quantification’, in: J. Law (ed.), *Power, Action and Belief: a New Sociology of Knowledge?* (London, 1986), 88-111.

[728]A few scientists could wax poetic about the beauty of light. Albert Michelson, for example, using rhetoric typical of turn-of-the-century popular scientific works, lamented his inability to describe light and colour as clearly as could an artist: ‘I hope that the day may be near when a Ruskin will be found equal to the description of the beauties of coloring, the exquisite gradations of light and shade. . . which are encountered at every turn’ [A. A. Michelson, *Light Waves and Their Uses*, (Chicago, 1901), 1-2]. Even he devoted his energies, when not popularising his work for the general public, to quantifying light, however. For an overview of the changing mental models of light, see A. Zajonc, *Catching the Light* (New York, 1993).

A third determinant in the convergence of practice was the portrayal of light as a particular manifestation of electromagnetic radiation.[729] Colorimetry (mapping the effect of particular wavelengths of radiation on visual perception) came to be viewed as a sub-set of photometry (defining and measuring the intensity of 'white', or eye-averaged, radiation) which was in turn seen as a particular case of the more general practices of radiometry (measuring the intensity of radiations of any wavelength). Such a hierarchical linking carried implications about what constituted valid methods of observation and analysis. Interpreting the human eye merely as one form of energy detector strongly supported the argument for physical methods. Through the 1930s the subjects of photometry, colorimetry and radiometry were increasingly being lumped together.[730] By the end of the decade the consolidation of practice was nearly complete: although Germany had long resisted change in standards of light intensity, it adopted a platinum-based standard along with France, America and Britain in the early months of the Second World War, on New Year's Day, 1940.[731]

The changes in the practice of light measurement during the early twentieth century can also be characterised as a transition towards an increasingly co-operative

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[729]For example, the opening pages of W. E. Barrows, *Light, Photometry and Illuminating Engineering* (N.Y., 1938), detail respectively the electromagnetic spectrum, spectral energy distribution curves of light sources and the spectral sensitivity of the eye. This format became *de rigeur* for books on colour by World War II.

[730]W. E. Forsythe (ed.), *Measurement of Radiant Energy* (N.Y., 1937), and P. Moon, *The Scientific Basis of Illuminating Engineering* (N.Y., 1936). Forsythe, working at the Incandescent Lamp Department of GE at Nela Park, brought together scientists specialising in radiometry, photometry and colorimetry for his book. This can be seen as the product of a 'culture of unification' which had been nurtured at Nela Park since its foundation, owing to the research policies of its first directors. Similarly Moon, an illuminating engineer and relative outsider to the scientific community, attempted to broach the separation by allying illuminating engineering with scientific principles.

[731]This was essentially the long-sought Violle standard, first proposed in 1881 and actively pursued by the PTR, NPL and others from the 1890s. Formal international ratification was, however, delayed by the war and did not occur until 1948. See J. W. T. Walsh, 'The new standard of light', *Trans. Illum. Eng. Soc.* 5 (1940), 89-92, and O. C. Jones and J. S. Preston, *Photometric Standards and the Unit of Light* (London, 1969).

enterprise involving progressively larger groups of practitioners. This emergence of collective activity did not represent merely a rising popularity for increasingly standardised techniques, but rather the growing organisation of separate communities. The growth of organisation among academic scientists has been discussed, for example, by Donald Cardwell, who attributes the British case to 'a highly successful take-over bid for science and scholarship generally' by universities, converting the subject from the domain of amateurs to career educators and researchers.[732] This interpretation neglects the utilitarian concerns that motivated the development of light measurement. More pertinent illustrations concentrating on the case of American and British electrotechnics have been given, for example, by David Noble, Thomas Hughes and Graeme Gooday.[733]

Driven by diverse motives, the new organisations marshalled significant numbers of investigators and fostered links between communities. Thus technical delegations strove to define standards for lighting (involving, for example, the Illuminating Engineering Societies, the NPL and the NBS); manufacturing applications impelled the intensive research of colorimetry (e.g. at the NELA laboratory, the Munsell company, and through the sponsorship of the OSA and the

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[732]Until the turn of the twentieth century, British photometry in particular, and British science in general, was nearly devoid of organisation and government support. Cardwell refers to a '*fin de siècle* lassitude' in British science, which he ascribes to the diversion of interest from science and technology during the 'age of imperialism'; strangulation of scientific enthusiasm by an oppressively time-consuming examination system; and, excessive specialisation with little attention paid to applied problems [D. S. L. Cardwell, *The Organisation of Science in England* (London, 1972), 191].

[733]D. F. Noble, *America by Design: Science, Technology and the Rise of Corporate Capitalism* (N.Y., 1979), T. P. Hughes, *Networks of Power: Electrification in Western Society 1880-1930* (Baltimore, 1983) and G. Gooday, 'Teaching telegraphy and electrotechnics in the physics laboratory: William Ayrton and the creation of an academic space for electrical engineering in Britain 1873-1884', *Hist. Technol.* 13 (1991), 73-111. Noble discusses how 'during the closing decades of the nineteenth century, the new institutions of science-based industry, scientific technical education, and professional engineering had gradually coalesced to form an integrated social matrix (composed of the corporations, the schools, the professional societies)' [p. 50]. Hughes' 'systems approach' emphasises the interplay of interests beyond those of academic scientists. Gooday documents the transition of electrotechnics from an engineering craft to academic subject.

CIE); governments promoted competitiveness in international trade (e.g., through the DSIR in Britain); and, industry sought new markets by developing and marketing photoelectric physical methods (particularly at major electrotechnical companies such as GEC and Westinghouse).[734]

Social constructivism as a model

As illustrated in previous chapters, light measurement can be depicted plausibly as a subject shaped by socially mediated processes. This is perhaps unsurprising for a subject which, at heart, relies upon the relationship between the practitioner and human sources of data.[735] The most widely accepted models of scientific development still accepted by most scientists, however, (i.e. the models of Karl Popper and Thomas Kuhn) neglect the role of peripheral subjects such as photometry and colorimetry, denying their place in the taxonomy of science altogether.[736] This case study supports a social constructivist interpretation, which

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[734]New technology encouraged organisation at a different level. The once tenuous links between national and commercial laboratories were strengthened; the shifting of personnel between the NPL and the GEC Research Laboratory, and between the NBS, NELA Research Laboratory and Munsell Company are examples of this. The connections between industry and government assisted the rapid promulgation of new technology in international standards through the CIE. Thus standards of photoelectric intensity measurement were tabled at CIE meetings in the early 1930s, less than a decade after their development.

[735]A feature shared with the related subject of psychology; see K. Danziger, *Constructing the Subject: Historical Origins of Psychological Research* (N.Y., 1994), 8-10.

[736]Popper emphasises the interplay between hypothesis and its experimental refutation in scientific advance, stating that ‘knowledge can grow, and science can progress – just because we learn from our mistakes’ [K. Popper, *Conjectures and Refutations* (London, 4th ed. 1972), vii]. Such an interplay ‘takes us nearer to the truth’, because, for Popper, science is solely a fact-finding enterprise to *discover truth*. While observing that ‘the growth of scientific knowledge may be said to be the growth of ordinary human knowledge *writ large*’, he downplays the social factors in the creation of scientific knowledge [*ibid.*, 216]. From this perspective, applied science and technology are merely applications of hard-won facts. Issues central to the field of light measurement – the roles of communities of practitioners, technological innovation and cultural pressures – receive scant attention. Indeed, light measurement can be assimilated only with difficulty into the Popperian view of science. The second and more recent picture originates

contends that cultural circumstances can determine not only the direction taken by a science, but also its very structure and content.[737] In so doing it goes beyond the sociology of science championed by Robert Merton.[738] In the Mertonian view, cultural factors can determine the choice of scientific topics studied, the methods employed and the investigators who study them, and thus select which facts, from the

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with Kuhn, who sees science as a series of 'normal' periods interspersed with revolutions of the scientific orthodoxy [T. S. Kuhn, *The Structure of Scientific Revolutions*]. 'Normal' science, a cumulative process of accreting new facts onto an existing theoretical framework, is interrupted when the scientific community decides collectively that new facts can no longer be incorporated. At this point, a new framework is established that replaces in whole or in part the old one. The change in world view may redefine which 'facts' are important and make the previous views incomprehensible. The importance of the social component in this scientific development is evident. Indeed, Kuhn stresses that 'scientific knowledge, like language, is intrinsically the common property of a group or else nothing at all. To understand it we shall need to know the special characteristics of the groups that create and use it' [*ibid.*, 210]. His analysis nevertheless centres on theory rather than experiment and practice. For Kuhn, experimental science is an adjunct rather than a central component of scientific advance. His history of the blackbody laws, for example, stresses the development of theories to the almost complete exclusion of experiment – a case which David Cahan has convincingly shown to have been motivated by utilitarian concerns [T. S. Kuhn, *Blackbody Theory and the Quantum Discontinuity* (Oxford, 1978) and D. Cahan, *An Institute for an Empire: the Physikalisch-Technische Reichsanstalt 1871-1918* (Cambridge, 1989), Chap. 4]. More particularly, Kuhn's views of quantification relegate it to a secondary role in the development of science. In normal science, he argues, measurements reveal 'no novelty in nature', but merely make explicit 'a *previously implicit* agreement between theory and the world' [T. S. Kuhn, 'The function of measurement in modern physical science', in: H. Woolf (ed.), *Quantification* (Indianapolis, 1961), 31-63; quotation p. 41 (author's italics)]. This view neglects the role of quantification in making possible a discourse – in providing a language of description and comparison. Light measurement in Kuhnian terms is distinctly peripheral in scientific importance, fulfilling at best a verificatory role.

[737] See Chapter 1, footnote [23] for references. Recently, multiple meanings of social constructivism have limited its ability to be discussed or tested against case studies. As in the practice of science itself, theoretical or phenomenological models must be subservient to evidence; the historical evidence incorporates more nuances than any model can hope to reveal. For a recent critique addressing this point, see S. Sismondo, 'Some social constructions', *Soc. Stud. Sci.* 23 (1993), 515-31.

[738] E.g. R. K. Merton and J. Gaston, (eds.), *The Sociology of Science in Europe* (Carbondale, 1977).

pool of ‘natural’ knowledge, are discovered. Social constructivists add that the resulting knowledge is itself culturally moulded – that things, in the words of John Law, ‘might have been otherwise’.[739] The significance of this social shaping is seen most clearly in the case of colour, in which the complexities of human perception were progressively simplified and normalised to make them amenable to quantification, a goal having particular value in twentieth-century mass-production society. Similarly, physical photometry was socially transformed from a complex technology dubiously related to visual perception into a powerful means of automating industrial processes. This ‘seduction of simplifications and conventions’ may be a more ubiquitous feature of knowledge-production than generally acknowledged.[740]

The social perspective can be extended further for fresh insights. Bruno Latour and Michel Callon, for example, have attracted considerable attention with their elaboration of an ‘actor-network’ theory of scientific development. In the language of Callon all factors influencing the practice and development of a science are ‘actors’ that interact through ‘networks’.[741] These actors and networks operate at many levels: for the subject of light measurement some of the principal actors are the CIE, the human eye, incandescent lamps, Alexander Trotter and photometers. The networks comprise interactions of varying importance between humans, instititutions, instruments and the scientific subjects. The inclusion of non-human factors as protagonists in a story couched in terms of battles of control is what distinguishes the Latourian perspective from social constructivism *per se*.[742] Indeed, to limit the

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[739]J. Law (ed.), *A Sociology of Monsters: Essays on Power, Technology and Domination* (London, 1991), 1-23. Law suggests that a sociology of special cases, or ‘monsters’, is required to deal with the myriad differences between heterogeneous case studies.

[740]For the case of the construction of valid tests of water quality, see C. Hamelin, *A Science of Impurity: Water Analysis in Nineteenth Century Britain* (Berkeley, 1990); quotation p. 40.

[741]E.g. M. Callon, J. Law and A. Rip, ‘Glossary’ and ‘How to study the force of science’, in: Callon *et. al.*, *Mapping the Dynamics of Science and Technology: Sociology and Science in the Real World* (London, 1986), xvi-xvii and 3-18.

[742]More restrained accounts of social constructivism are espoused, for example, in the work of Trevor Pinch and Harry Collins.

analysis to human actors – to the social dimension – is as misleading as restricting it to a discussion of mere technology, suggests Latour.

Perhaps Latour's most fertile theme is his claim that historians often mistake the *direction* and *complexity* of cause-and-effect relationships.[743] Thus the monitoring of gas supplies for illuminants and the changing emphases in astronomy influenced the technologies adopted for comparing light intensities rather than vice versa.[744] Similarly, the creation of photometric standards made possible the growth of new scientific communities, rather than being a consequence of co-operating, pre-existing communities. And instead of the properties of human perception solely defining the single, 'correct' science of colorimetry, the subject was shaped also by social, technological and historical factors. Opposite to our expectations, colorimetry defined which aspects of human colour perception were deemed significant, and which should be ignored.

While Latour's model is not contradicted by the case of light measurement, neither is it strongly confirmed. In particular, Latour's emphasis on the enduring importance of the laboratory as a key feature of scientific development seems of limited relevance here. He has argued, for example, that Pasteur was able to convince his critics of his microbial research by converting cow fields into laboratories, where experimental variables could be strictly controlled.[745] In the case of light measurement, however, the content of the laboratory was a minor weapon in the armoury of competing practitioners. Indeed, the issue of competition is curiously under-represented in this peripheral subject. Points of contention, such as a recognition of a *need* to quantify light, and the utility of human *vs.* physical measurement, were played out over decades during which the scientific communities changed as much as did the questions they posed.

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[743]See B. Latour, *Science in Action* (Cambridge, MA, 1987),. 7-14.

[744]That is, photometry during this period was impelled by the cultural invention of problems – the 'need' for stable gas supplies and for reliable catalogues of stellar magnitudes, respectively – rather than by the availability of new technology.

[745]B. Latour, *The Pasteurization of France* (Cambridge, MA, 1988).

Historical change is also unsatisfactorily described. In discussing how technoscience is shared between large and small actors, Latour suggests that the trend is inevitably towards agglomeration and the eventual control of a subject by players that can marshal the greatest resources; small countries, for example, lack autonomy.[746] Replacing the word *country* by *astronomical community* or *illuminating engineering fraternity*, however, it is clear that this trend is not universal. Communities need not merge or even grow into internally sufficient entities to control a subject. They merely mutate the subject to suit their own ends.[747] Thus light and colour measurement, which consistently failed to achieve autonomy, are inadequately described in Latourian terms.

Peripheral science

The *immiscibility* of communities noted above is an enduring feature of light and colour measurement. From the late nineteenth century to the Second World War light and colour measurement fitted imperfectly into the disciplinary map. Neither scientists nor engineers claimed the subject as their own. What qualities relegated the subject to the margins of scientific discourse? In what ways was light measurement different? In this section I examine themes previously addressed by historians and sociologists, define the key qualities of light measurement as a *peripheral science*, and give some tentative examples.[748]

On being at the edge

Light measurement was, over the period covered in this work, ‘on the side-lines’, and ‘on the borderline of interest’ rather than ‘at the frontier of knowledge’. That is, it occupied a region between recognised sciences (e.g. quantum mechanics or

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[746]Latour, *op. cit.* [19], 167.

[747]Ends such as the pragmatic and particular scale of magnitude adopted by astronomers, or the colour charts employed by bird fanciers or automobile manufacturers. These communities experienced no pressure to converge as long as their goals of quantification were expressed in particular and local terms.

[748]The *classification* of subjects is, itself, a matter of social construction. In this respect the methodology of this thesis inevitably is embedded in the subject it treats. As the case studies have shown, however, the partitioning of a continuum, while artefactual, is a common strategy that can yield useful insights.

hydrodynamics) and something else, identified by its practitioners alternately as a technique, a technology or an applied science. By demarcating a boundary, it contrasted 'real' science and these related subjects.

Previous definitions of peripheral science have been varied and have not addressed the same combination of characteristics. Alphonse de Candolle used the term in the geographical sense when he wrote of 'peripheral or newly civilised countries'.[749] Elisabeth Crawford extends his analysis by 'division of the world of science into centre (or centres) and periphery'.[750] Mary Jo Nye also takes up this theme in discussing French 'provincial' science.[751] Alternatively, the periphery can refer to economic or social properties. T. Schott denotes a peripheral science as one in circumstances of inadequate funding or resources.[752]

Some definitions of 'marginal' science have been proposed having resonances with 'peripheral'. For Thomas Gieryn and Richard Hirsch, a scientist is 'marginal' if young or if recently migrated from another field.[753] They cite an earlier definition of a marginal scientist as one who is 'a cultural hybrid. . . living and sharing intimately in the cultural life and traditions of two distinct people'.[754] Jonathan Cole and Harriet Zuckerman have explored this definition, distinguishing between those subjects that are consistent with a 'central discipline', such as molecular biology or sociobiology, and those that are 'cultural hybrids' spanning science departments. They suggest that the hybrid type encounters more initial resistance from practitioners than the

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[749] A. de Candolle, *Histoire des Sciences et des Savants Depuis Deux Siècles* (Geneva, 1885).

[750] E. Crawford, *Nationalism and Internationalism in Science, 1880-1939* (Cambridge, 1992), 18-23 and Chap. 4.

[751] M. J. Nye, 'The scientific periphery in France: the Faculty of Sciences at Toulouse (1880-1930)', *Minerva* 13 (1975), 374-403.

[752] T. Schott, 'International influence in science: beyond center and periphery', *Soc. Sci. Res.* 17 (1988), 219-38. This author also defines peripheral in a geographical sense, as 'away from the centre of research' for countries deprived of adequate resources, rather than as entire subjects isolated from mainstream science.

[753] T. F. Gieryn and R. T. Hirsch, 'Marginality and innovation in science', *Soc. Stud. Sci.* 13 (1983), 87-106.

[754] Robert Park, quoted in *ibid.*, 88.

'centrally based' type.[755] Nevertheless, their case studies invariably show that the hybridisation is transitory; the fields inevitably coalesce to form self-contained disciplines. Similarly, David Edge and Michael Mulkay cite three forms of marginality in the early history of radio astronomy, a field recognised as a discipline within two decades of its emergence.[756]

These previous analyses are inadequate for discussing light measurement. The equating of peripheral science as 'new science' is inappropriate, because photometry remained a 'science on the side-lines' for the entire period covered here (and arguably remains so today). Such a subject is not necessarily a precursor of other states, e.g. a 'pre-academic science' or 'emergent technology'. Rather than being a phase in the evolution towards maturity, my 'peripheral' science can retain its separate nature indefinitely.

Of course, the use of the terms 'peripheral' or 'marginal' requires a counter-definition corresponding to 'central'. By central or disciplinary science I mean subjects that have gained intense scientific attention, and have possibly formed a discipline or at least have been investigated by a coherent, self-recognised body of practitioners. Such a subject conforms closely to the traditional historiographical definitions of science. A peripheral science, on the other hand, does not form a discipline or develop research schools. Indeed, it could be argued that 'pure' (as opposed to 'applied') science is a recent phenomenon, and that peripheral science is a

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[755] J. R. Cole and H. Zuckerman, 'The emergence of a scientific specialty: the self-exemplifying case of the sociology of science', in: L. A. Coser (ed.), *The Idea of Social Structure* (N.Y., 1975), 139-74.

[756] D. O. Edge and M. J. Mulkay, *Astronomy Transformed: the Emergence of Radio Astronomy in Britain* (N.Y., 1976), 362-3. The marginal characteristics include: (i) initial discovery by an 'applied' scientist indirectly linked to the 'basic' research networks; (ii) wartime discoveries of academic scientists that then seeded academic research; and (iii) the introduction of new astronomical techniques by researchers trained as physicists, studying problems not initially identified as astronomical. Disciplines, and their relationship to peripheral science, are discussed below.

more typical, if neglected, case.[757] I suggest that light measurement is an example of a general form of science in the modern period.[758]

An undisciplined science?

The failure to achieve autonomy was a central characteristic of the subject of light measurement, and one that sets it apart from disciplinary sciences. Previous sociological studies of scientific disciplines reveal the particularities of this case study. To paraphrase G. Lemaine *et. al.*, disciplines during early stages loosely define the research problems, and results are open to widely differing interpretations. With specialisation, agreement tends to increase, consensus grows, publications occur in more specialised journals, the proportion of references by authors not centrally engaged in research declines markedly, and a small number among the many early papers come to be viewed as paradigmatic and get cited regularly. Research areas develop in response to major innovations, as well as from government support and university expansion programmes. The rate, direction and intellectual content of development depend on such social factors.[759] This list of attributes accords only weakly with the history of light measurement, which corresponds only to the first of the preceding stages. At best, it appears as a discipline suffering arrested growth.

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[757]Michael Dennis, in discussing corporate laboratories, has argued persuasively that the very definition of 'pure' and 'applied' science is a construct of the early twentieth century, which accompanied the shift of academic scientists from a primarily pedagogical role to research. He attributes the ascendancy of this definition to Robert Merton, whose sociology of scientists was based on seventeenth century natural philosophers and who later 'described the goals of élite university scientists', thereby excluding the industrial researcher [M. A. Dennis, 'Accounting for research: new histories of corporate laboratories and the social history of American science', *Soc. Stud. Sci.* 17 (1987), 479-518; quotation p. 492]. Dennis notes that disciplinary research projects did not survive in corporate settings such as General Electric and Bell, as was the case for the subject of light measurement.

[758]Say from 1850 to the present. Key features that became established during the 'modern period' are the growth of science-based industry, the professionalisation of science and the institutionalisation of scientific research. This predominant form of science in the twentieth century, emphasising applied science and science-based technology, includes peripheral science as a sub-category.

[759]G. Lemaine, R. McLeod, M. Mulkay & P. Weingart (eds.), *Perspectives on the Emergence of Scientific Disciplines* (The Hague, 1976), p. 6.

As noted above for the case of radio astronomy, it has been common to postulate a connection between discipline formation and the maturity of a subject.[760] According to this model, 'specialties' eventually and inevitably evolve into disciplines. John Law, for example, identifies three types of specialty and distinguishes between 'mature' and 'immature' specialties. A 'methods-based' specialty such as X-ray crystallography is defined 'on the basis of shared scientific gadgetry'; 'theory-based' specialties have a shared formalism; and, 'subject-based' specialties have members working on a particular subject matter.[761] Law suggests that the first two of these are later stages in development than the third. Such an evolutionary path is inappropriate for peripheral science. While the subject of light measurement arguably could be labelled as a subject-based specialty, it cannot be said to have achieved 'maturity on a basis of shared methods' or 'on a basis of shared theories'.[762] Despite the shared subject matter, and the eventual practical consensus on photoelectric techniques, light measurement has remained a tenuously defined 'specialty' – but it does not follow that this makes it immature. In the same vein, Nicholas Mullins denotes Law's former two cases as being at the 'cluster' stage, and the latter as at the 'network' stage, with specialties seen as growing from nuclei of researchers bound by communications, colleagueship and co-authorship.[763] Having successfully traversed these stages, he says, a subject becomes a specialty, 'an institutionalised cluster which has developed regular processes for training and recruitment into roles which are institutionally defined as belonging to that specialty'.[764] These prior studies have all stressed the importance of an academic nucleus, if not in the early emergence of a new phenomenon, then in its development

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[760] *Ibid.*

[761] J. Law, 'The development of specialties in science: the case of X-ray protein crystallography', *Sci. Stud.* 3 (1973), 275-303.

[762] *Ibid.*, 303.

[763] N. C. Mullins, 'The development of a scientific specialty: the phage group and the origins of molecular biology', *Minerva* 10 (1972), 51-82, and 'The development of specialties in social science: the case of ethnomethodology', *Sci. Stud.* 3 (1973), 245-74.

[764] *Ibid.*, 274.

into a coherent discipline.[765] The emphasis on clustering highlights the insufficiency of Mullins' model for peripheral science: it is the lack of a single centre that distinguishes light measurement from the case studies that these authors cite.

Technique, technology or applied science?

If a peripheral science lacks the central attributes of an academic science, is it, then, merely technology? I have used the term in previous chapters to describe aspects of the subject, but it is inadequate to characterise it fully. Previous attempts to distinguish science and technology, e.g. by Derek de Solla-Price, have been unconvincing, and this is particularly so for light measurement.[766] In distinction to his definition of technology, the field of light measurement was arguably a 'papyrocentric' activity and one closely associated with astronomy and spectroscopy, although lacking both discipline and an active network of co-citation. More recently, Barry Barnes has argued that, in any case, science and technology cannot easily be separated, and that neither is subordinate or wholly reliant upon the other.[767] The subject of photometry also lacks some of the characteristics commonly associated with technology such as developing primarily in response to market forces. Light measurement cannot be relegated to mere technology or tool-making because only in the latter part of the period studied (after 1920) was some photometric research funded solely and directly for commercial ends (e.g. GEC phototube research); several aspects of the subject had little commercial or industrial motive, for instance

[765]Edge and Mulkay [*op. cit.*, 356-7] describe the early history of radio astronomy in terms of several co-operating academic research groups which differentiated the scientific problems selected.

[766]De Solla-Price cites technology as having features including (1) little or no discipline, i.e. lacking professionals trained in universities by other 'experts', dedicated journals, literature dominated by a close-knit group of co-citators and neglect of archival literature; (2) literature centred on catalogues, handbooks, etc.; and (3) little influence on mainstream science [D. J. de Solla-Price, 'Is technology historically independent of science? A study in statistical historiography', *Technol. & Culture* 6 (1965), 553-68.

[767]B. Barnes, 'The science-technology relationship: a model and a query', *Soc. Stud. Sci.* 12 (198), 166-72.

photographic photometry.[768] Furthermore, unlike pure technologies, peripheral science does not develop a coterie of professionals. For example, light measurement could not be described as engineering, because the training and licensing of practitioners remained sporadic and uninfluential in its development. Of course, the definition of a ‘technology’ can be widened to include most of the learned and skilled activities of human life, but this merely dilutes the term to the point of meaninglessness. For the same reasons, the term ‘technoscience’ popularised by Bruno Latour is not sufficiently specific.[769]

To a few practitioners, light measurement was merely a *technique* to be *applied* to problems. This definition is ultimately unsatisfactory because of the breadth of methods employed, the range of problems studied, and the variety of investigators who used them. It minimises the scope of the subject and neglects its pretentions for the status of a science.[770] This is illustrated clearly by the case of colorimetry, which until the 1930s had little reliance on elaborate observing techniques or apparatus. Rather than being centred on a particular technique or apparatus, colorimetry was defined by its goal.

Is peripheral science, finally, just another term for applied science? The primary difficulty with the term *applied science* is its implicit assumption of a direction of development, i.e. scientific discovery followed by practical application. Such a categorisation also frequently implies an inadequate or unsuccessful science. D. S. L. Cardwell is dismissive in his description of many early twentieth-century career practitioners as members of a hitherto non-existent ‘rank and file’, with applied scientists often ‘of the second and third rank’. He tempers this, however, with the statement that ‘researches of the applied scientist are guided not by purely scientific

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[768]Commercial products such as microdensitometers were introduced in response to market demand.

[769]See B. Latour, *op. cit.* [19], 157-9, 174-5. Latour uses *technoscience* as an all-encompassing term to include not just technology and science, but the networks that make them possible.

[770]E.g. by J. Walsh, who as a Division leader of the NPL perhaps not surprisingly referred to photometry as an *applied* science and a branch of technical physics. Edward Hyde, first director of the Nela laboratory, denoted it one of the ‘great middle fields of science’ (see chap. 5, ref [108)].

considerations, but by the requirements of industry. . . this does not mean that the applied scientist and technologist are. . . truncated scientists'.[771] I suggest that peripheral science is not merely technology or applied science, nor a subject of lower intellectual stature. Instead, it is a qualitatively different enterprise; much of technology is peripheral to science and vice versa. Rather than being invariably linked with technology or applied science, peripheral science is a distinct and persistent category that shares some of their attributes, but evincing distinct developmental features.

Attributes of peripheral science

Some of the identifiable characteristics that place a peripheral science outside the traditional views of a scientific discipline as characterised by historians of science are:

1) a lack of autonomy and authority over the subject by any one group of practitioners;
2) a persistent straddling of disciplinary boundaries;
3) a lack of professionalisation among the subject's practitioners;
4) a continuous and changing interplay between technology, applied science and fundamental research.
5) generally slower and less active evolution than its scientific contemporaries; failure to thrive.

These points are inter-related and follow from one key feature: the sharing of the subject between distinct scientific communities.

1) lack of autonomy and authority by any one group of practitioners

The absence of 'ownership' by a single community deprived light measurement of a clear definition and purpose. Without focus, it was both shared and unclaimed, retarding its standardisation or integration into a coherent perspective.

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[771] D. S. L. Cardwell, *op. cit.* 229, 235.

Case studies displaying the sharing of control between communities have, in previous historical analyses, evoked dichotomies: technology *vs.* science, internal *vs.* external influences, or theory *vs.* experiment. For example, the idea of two communities – e.g. ‘practical engineers’ versus ‘academic engineers’ and scientists – has been proposed for the situation of the subjects of refrigeration/thermodynamics in Germany, and British chemistry at the turn of the twentieth century.[772] Nevertheless, such simplistic dichotomies can come at the price of historical accuracy. For light measurement, at least, such two-way splits of influences could be postulated only for limited time periods or subject areas, if at all.[773] Far from being determined by a playing-off of rival influences, the subject depended on the sporadic attentions of several communities.

2) persistent straddling of disciplinary boundaries

A *discipline* can be defined briefly as a subject based on systematic knowledge, and uniting its practitioners in a self-regulating system of training and intellectual approbation. The key elements are *self-definition* by the practitioners and *external recognition* by non-practitioners. Lacking both these features, photometry and colorimetry certainly never developed into disciplines.[774] Its practitioners did not

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[772]See H.-L. Dienel, ‘Industrial refrigeration in Germany 1870-1930: interactions between two engineering subcultures’, *Conference on Technological Change* (Oxford, 1993). University researchers approached refrigeration from the point of view of thermodynamic theory, and spent considerable time in consultancy work, acting as ‘science notaries’ to validate practical research. The working engineers employed empirical methods to select the best form of refrigeration technology. For a similar case of the negotiation between emergent communities in academic and industrial chemistry, see J. F. Donnelly, ‘Representations of applied science: academics and the chemical industry in late nineteenth-century England’, *Soc. Stud. Sci.* <u>16</u> (1986), 195-234.

[773]E.g.: Victorian gas inspectors *vs.* astronomers; visual *vs* physical methods of photometry *c*1900-20; optical *vs.* electrical engineering traditions in photometry; industrial *vs.* governmental laboratories *c*1910-30; physicists *vs* psychologists in colorimetry between the wars.

[774]The situation of international colorimetry in the early twentieth century was reminiscent of that in German research into colour *perception* during the late nineteenth century. As R. S. Turner has noted [‘Paradigms and productivity: the case of physiological optics, 1840-94’, *Soc. Stud. Sci.* <u>17</u> (1987), 35-68; quotation p. 43], ‘it never constituted a true disciplinary grouping. Vision studies *per se* (as opposed to medical applications) never achieved institutional recognition in the

adopt any specific term for the field which found itself practised in such diverse contexts – individual departments of electrotechnics, gas engineering and optics. Borrowing elements from one another and shifting definition, these peripheral subjects have defied classification by both practitioner and historian. This lack of cohesion is a characteristic that persists for these subjects to the present day. The difference between 'disciplinary' and 'undisciplined' science has been discussed above.

3) lack of professionalisation

The distinctions between an *occupation* and a *profession* have been discussed in the context of illuminating engineers in Chapter 4. These practitioners did not attempt to define themselves either as professional engineers or as scientists of a distinct specialty.[775] The discussions of this point at the early Illuminating Engineering Societies reveal that their members' aversion to such labels stemmed from a lack of confidence in their body of knowledge as a coherent subject, and from their disparate backgrounds. The new members voiced their wish to encourage research and communication, and the concern that their differing vocations would impede this goal. A profession, involving career and societal characteristics in addition to the intellectual features of a discipline, is unlikely to develop where a discipline does not. The lack of professionalisation is thus a consequence of the disciplinary straddling of a peripheral science.

European universities, never possessed a journal addressed exclusively to its concerns, and never generated arguments for its methodological or philosophical autonomy *vis-à-vis* other branches of science. Likewise, virtually none of its practitioners pursued vision research to the exclusion of other problems. Instead, researchers from several legitimate disciplines contributed to the study of vision.' Thus peripheral sciences may spawn others, as colour perception, colour measurement and photometry shared similar features.

[775]Illuminating engineers and photometrists were often on the outskirts of the developing hierarchies of science and of industry. R. Torstendahl ['Engineers in industry, 1850-1910: professional men and new bureaucrats. A comparative approach', in: C. G. Bernhard, E. Crawford and P. Sörbom (eds.), *Science, Technology and Society in the Time of Alfred Nobel* (Oxford, 1982), 253-70] argues that the professionalisation and career differentiation of groups of employees, such as the electrotechnicians at Siemens & Halske, was contingent on their firms devoting resources to research and development. Only a handful of illuminating engineers thus found career definition through this industry- and government-sponsored bureaucratisation.

4) changing interplay between technology, applied and pure science

A 'seamless web' of influences is appropriate to describe peripheral science. Occupying a nexus between more easily identified subjects, it borrows from each, its position on the science / technology divide both drifting with time and depending on the perspective of the observer. The social networks are transient, 'coalescing briefly around single theoretical and technical problems they share[d] for brief periods, as passing aspects of longer term goals'.[776] In a subject not driven by theoretical impetus, social factors, too, play a decisive role. The applicability of a social constructivist interpretation has been discussed above.

5) less active evolution than its scientific contemporaries; failure to thrive

A subject unnurtured by an active scientific community inevitably languishes; a technique of limited or unappreciated utility is abandoned or under-utilised. As the epilogue describes, the status of light and colour measurement fell once the central concerns were satisfied and techniques were rendered routine.

Some examples

Having defined the nature of peripheral science, what other subjects (if any) correspond to this definition? A detailed examination of other peripheral subjects is beyond the scope of this thesis, but some examples can tentatively be identified. A careful comparison of these and other topics with light measurement would be useful in further refining the definition of peripheral science.

Topics excluded from peripheral science are straightforward to find, because they incorporate features that peripheral science has been defined to lack. *Scientific disciplines* such as quantum mechanics and thermodynamics are practised by relatively homogeneous communities trained in academic environments. *Engineering professions* such as mechanical, electronic and civil engineering are self-circumscribing groups regulated by legal status. *Technologies* such as sound reproduction have a diverse assortment of practitioners but a primarily pragmatic, rather than scientific, motivation.

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[776]Edge & Mulkay, *op. cit.*, 127.

Examples of potential peripheral sciences must be more carefully chosen to select those displaying *all* the features of the working definition. Some examples developing in the same period as light measurement include vacuum science, food science and instrument science.

i) vacuum science

The subject of vacuum creation and usage has only recently been labelled a 'science'.[777] The technology of vacuums, and the reasons for producing them, have changed dramatically since the late nineteenth century. Piston pumps, rotary mechanical pumps and then vapour jet pumps were used for evacuating incandescent bulbs, for vacuum metallurgy and for atomic physics research. The inventors and users of the techniques included distinct communities of scientists and engineers, frequently working in industry. These included Irving Langmuir, who designed an improved mercury diffusion pump at GE Research Labs, and O. E. Buckley, who developed an ionisation manometer at American Telephone & Telegraph Co. in 1916; J. Housekeeper, perfecting glass-to-metal seals at Western Electric Corporation in 1923; and C. R. Burch, using low vapour-pressure pump oils at Metropolitan-Vickers in 1928.[778] A close parallel to photometry, vacuum science developed as a collection of technologies and practices employed by separate communities of practitioners, none of which became professionalised nor solely controlled its development.

ii) food science

Sally Horrocks has recently written a history of the scientific aspects of the British food industry.[779] As was the case with light measurement, she finds continual and changing interactions between industry, government and university, shaped by technology, market demands and organisational characteristics. Her case study can be

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[777]The American Vacuum Society was founded in 1953 and marked its 30th anniversary with a retrospective *History of Vacuum Science and Technology* (N.Y., 1984).

[778]M. H. Hablanian, 'Comments on the history of the vacuum pump', *J. Vac. Sci. Tech. A*2 (1984), 118-25, and J. H. Singleton, 'The development of valves, connectors, and traps for vacuum systems in the 20th century', *J. Vac. Sci. Tech. A*2 (1984), 126-31.

[779]S. Horrocks, *Consuming Science: Science, Technology and Food in Britain, 1870-1939* (PhD thesis, Univ. Manchester, 1993).

readily identified in terms of peripheral science. Horrocks identifies three communities of food scientists: industrial investigators, scientists in government research establishments such as the DSIR, and academic researchers. As with academic colorimetry, this latter group is both transitory (often relying on postgraduate students) and diffuse, with only one or two university departments having recognisable programmes before the Second World War. Moreover, she observes that ‘food science would not be considered a successful academic subject before World War Two, and it was widely acknowledged that it was industrial companies not university researchers who were taking the lead’.[780] The little ongoing research was largely unco-ordinated and arose from particular institutional circumstances. Horrocks sees these communities, with their differences in personnel and approaches, as inter-related, ‘each group occup[ying] a distinct place in the process which brought their expertise to bear on the food supply’, but concludes that ‘the very notion of applied science, and how new knowledge is translated into commercial practice, requires detailed investigation’.[781] I would argue that the apparent co-operation of these communities was a consequence of their distinct research and operational niches, and would emphasise their lack of significant communication and inter-dependence.

iii) instrument science

Instrument science was a product of the late-nineteenth century interplay between scientists and industry in Germany.[782] It developed a self-awareness early on, furthered by dedicated journals such as *Zeitschrift für Instrumentenkunde.* Directed by a collection of practitioners with different goals, the subject never crystallised into an academic science; it was being reinvented and promoted in England as late as the 1950s. Defined as more than the mere application of physics to the measurement process, it incorporated the philosophy that instrumentation was worthy of study in its own right:

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[780]*Ibid.*, 282.

[781]*Ibid.*, 311.

[782]This term, adopted by English-speaking practitioners, is probably based on the German *instrumentenkunde*.

> In most cases, a scientific instrument is devised in the first place as a means to the end of making some physical phenomenon or quantity susceptible to observation or measurement, and once it has served this purpose nobody thinks very deeply about it again. Consequently, it is often tacitly accepted that 'in theory' an instrument should have a particular performance, but 'in practice' it does not. This however is not good science, which demands that if theory and practice differ, then one or both must be improved. Had Adams or Le Verrier been content to say that 'in theory' Uranus moves in a particular orbit but 'in practice' in a slightly different one, the planet Neptune would never have been discovered.[783]

As with light measurement, instrument science never became professionalised, although specialist practitioners became established. Instrument scientists were interdisciplinary, often supporting more than one research community.

These late nineteenth and twentieth-century examples, although little related in an intellectual sense, share the structural attributes of peripheral science. Other technical subjects sharing a large scientific component, diverse communities of practitioners and indistinct definitions of intellectual content include cryogenics,[784] computer science[785] and telecommunications[786]. Eda Kranakis cites, in addition, fields such as operations research, aerodynamics, cybernetics and teletraffic science under the rubric *parallel sciences*.[787] An investigation of the commonalities of these subjects might allow more nuanced studies of their twentieth-century evolution.

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[783]P. Fellgett, 'Three concepts make a million points', *Infr. Phys.* 24 (1984), 95-9.

[784]First referred to as 'cryophysics' in 1958. See F. E. Hoare, L. C. Jackson and N. Kurti (eds.) *Experimental Cryophysics* (London, 1961).

[785]Finding unsettled homes in physics laboratories, company finance departments and university applied maths curricula, the designation 'computer science' attached in the late 1960s has increasingly been replaced by 'information technology' and 'software engineering'.

[786]Perhaps differing from the other examples in being more goal-oriented, but otherwise sharing the structural features.

[787]See E. Kranakis, 'Technology, industry and scientific development', in: T. Längsmyr, *Solomon's House Revisited: the Organization aind Institutionalization of Science* (Canton, MA, 1990), 133-59, and E. Kranakis & L. Leydesdorff, 'Teletraffic conferences: studying a field of industrial science', *Scientometrics* 15 (1989), 563-91.

Epilogue: declining fortunes

Previous chapters chronicled the progressive organisation of light measurement by technical societies, research laboratories and appointed delegations. While these collective efforts encouraged a convergence of practitioners, the increased attention devoted to photometry and colorimetry by committees and industry was not sustained. The inter-war period saw both the ascent and decline of light measurement as a collective enterprise. Indeed, this dispersal of research effort is another illustration of the difference between peripheral science and coherent disciplines.

By the early 1930s the practice of illuminating engineering had become gradually less concerned with light measurement than with the design of lighting.[788] According to the President of the Illuminating Engineering Society of New York some two decades after its foundation, this was a natural consequence of the maturity of the subject. Sciences, he said, passed through three stages: (1) the observation of elementary phenomena, (2), the measurement and deduction of laws, and (3) the application of knowledge. The early years of the Society, he said, had concentrated on stage (2), and 'it was natural that the first ten years of the illuminating engineering movement should be occupied mainly in developing methods of measuring light'.[789] The evidence presented in this thesis refutes his simple sequence; indeed, 'elementary phenomena', 'measurement' and 'application' continued to mingle in photometric practice. Nevertheless, the measurement of light ceased to be of direct concern to the illuminating engineering community.

A similar *de*volution can be seen in the Society that provided the initial impetus for standardising light measurement: the Illuminating Engineering Society of

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[788] Where texts before WWI carried titles such as *Illumination and Photometry* [W. E. Wickenden (N.Y., 1910)], *Illumination: Its Distribution and Measurement* [A. Trotter (London, 1911)] and *Electrical Photometry and Illumination* [H. Bohle (London, 1912)], photometry was later relegated to single chapters in *Modern Illuminants and Illuminating Engineering* [L. Gaster and J. S. Dow (London, 1920)], *The Scientific Basis of Illuminating Engineering* [P. Moon (N.Y., 1936)] and *Illuminating Engineering* [W. B. Boast (N.Y., 1942)].

[789] J. S. Dow, 'Illuminating engineering: what it is and what it may become', *Illum. Eng. (NY)* 23 (1930), 295-8.

London merged with the Chartered Institution of Building Services Engineers as recently as 1980. The subject, once it had been rendered routine, failed to retain the interest of the originally high proportion of scientists, and was instead sustained by a coterie of career engineers. The subtitle of its periodical changed in the 1920s from *The Journal of Scientific Illumination* to *The Journal of Good Lighting*.

The inter-war period was the most active for research into heterochromatic photometry and colorimetry. With the contentious issues settled by delegations, attention devoted to these subjects declined considerably during and after World War II. An indication of its faltering status is given by the reduced emphasis at the National Bureau of Standards, where responsibility for colour research was reorganised seven times between 1948 and 1974, eventually devolving to become a part of the Sensory Environment Section of Building Research.

Similarly, the Commission Internationale de l'Éclairage continued to study colour standardisation after World War II, but limited this to relatively minor iterations of its 1931 work.[790] A loss of vitality in the CIE is suggested by the fiftieth anniversary meeting (Vienna, 1963) which reported the deaths of several past delegates including John Walsh, who had been associated with the Commission continuously from its origin.[791]

Despite the relative prominence given to light measurement in the inter-war period and its declining fortunes thereafter, the subject continued to exist, if not flourish. The decisive changes of the inter-war period had stabilised it to produce a generally recognised and definable subject. Light measurement was now based on physical measurement, and linked to human vision by agreed conventions concerning 'average' humans. Subsequent work at research laboratories centred on refining measurement technologies and psychophysical definitions, and in exploring further the visual characteristics that fell outside the prescribed areas. While these have modified the scientific understanding of the visual process, they have not significantly altered the self-circumscribed subjects of photometry or colorimetry. In a sense, then,

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[790]The '1931 standard observer' was revised and augmented in 1960, 1964, 1971 and 1976, most notably to include a wider field of view (10 degrees instead of the original 2 degrees).

[791]Compte Rendu CIE (1963), 12-3.

these subjects restricted their openness to subsequent change by adopting decisive standards. Subsequent commercial and scientific use then inhibited further change. This ‘self-limitation’ is a counter-example to the common case of the growth of scientific disciplines.[792]

Just as this peripheral subject spanned physics, technology and physiology, the quantity of light itself was found to be a shared property of the eye, instrument and energy. The continuing efforts to make quantitative light measurement useful – to promote the technique to Norman Campbell’s ‘class 3’ category – were motivated as much by a general desire to bring it into line with, and make it more directly a part of, the practices of modern physical science as by utilitarian need. To be a valid technical method in twentieth century physics and engineering was to be numerically sound. In this sense, the quantification of light can be seen as an attempt to reduce the peripheral status of the method and its practitioners. That the mathematisation of human perception remained limited must be ascribed ultimately to the conflicting goals of the relevant social groups.

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[792]E.g. Law, *op. cit.* and Mullins, *op. cit.*

APPENDICES

Appendix I
Increase in Publications on Light Measurement During the Nineteenth Century

A rough indication of the growth in interest in light measurement is given by the publication rate by decade. A readily-available source of this data is *The Royal Society Catalogue of Scientific Papers 1800-1900*, which provides the numbers of papers in subject categories defined by its indexers.[793] The Catalogue was chosen because it covered the entire nineteenth century, and because the entries were presumably chosen by one or a small number of indexers using fairly constant criteria for selection. An encouraging indication of the freedom of this source from bias towards British or English-language journals has been given by statistical studies by Mary and Thomas Creese.[794]

The subcategories chosen were those related to light measurement in Catalogue category 3010 ('Photometry, Units of Light'). In order to relate the growth in these publications to growth in other domains of physics, the categories were compared with two 'mature' subjects, *Mass & Density* (Catalogue category 0810) and *Gravitation* (Catalogue category 0700).

The numbers of papers published for all these subjects show a rise through the century, with, in most cases, a slight tailing off in the last decade. The subcategories show slight differences in growth; for example, publications on 'Intensity' rose gradually through the century, while 'Units of Light' showed a sharp increase in the last two decades.

In contrast to most of the 'photometric' subcategories, publications on 'Gravitation' and 'Mass & Density' exhibit a more gradually increase with time. It should also be noted that the number of publications in light measurement was a

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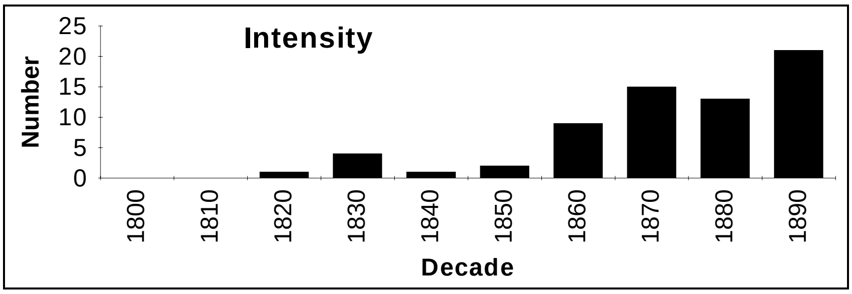
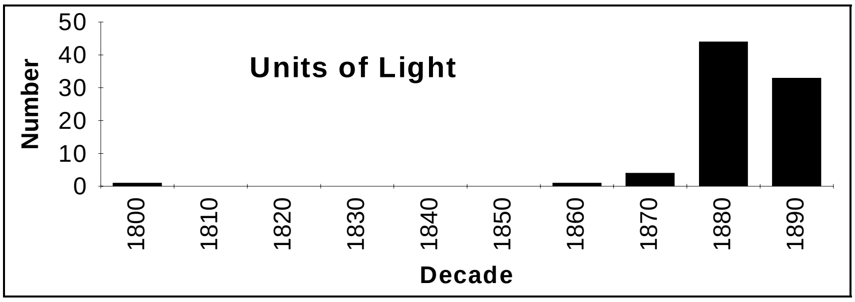
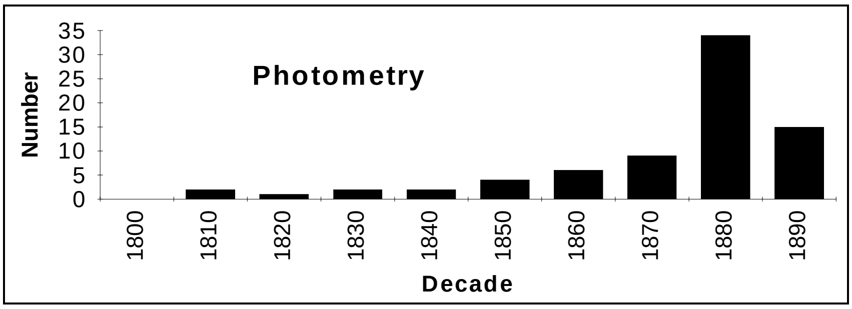
[793] Royal Society, *The Royal Society Catalogue of Scientific Papers 1800-1900, Subject Index Vol III, Physics, Part I* (Cambridge, 1912).

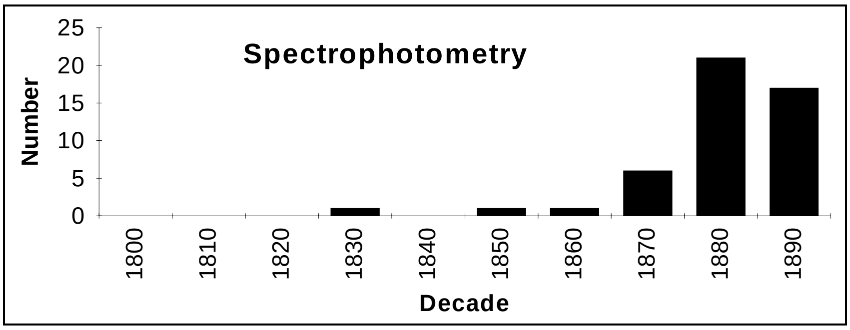
[794] M. R. S. and T. M. Creese, 'British women who contributed to research in the geological sciences in the nineteenth century', *BJHS* 27 (1994), 23-54, Appendix 2.

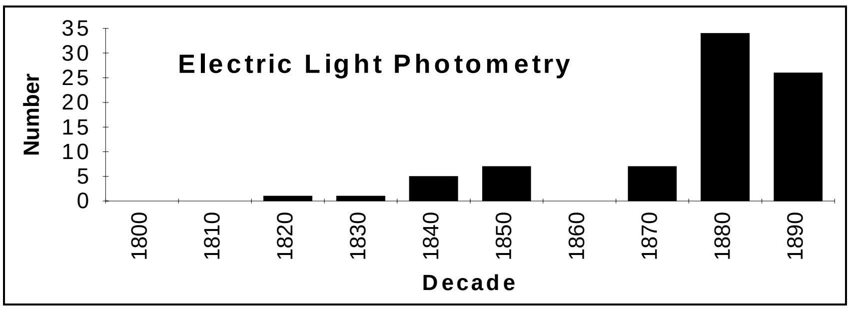
relatively high: some 1.5 times higher than for ‘Mass & Density’, and about six times higher than for ‘Gravitation’. The data suggest that the measurement of light intensity was a relatively expanding subject in physical science during the last two decades of the century.











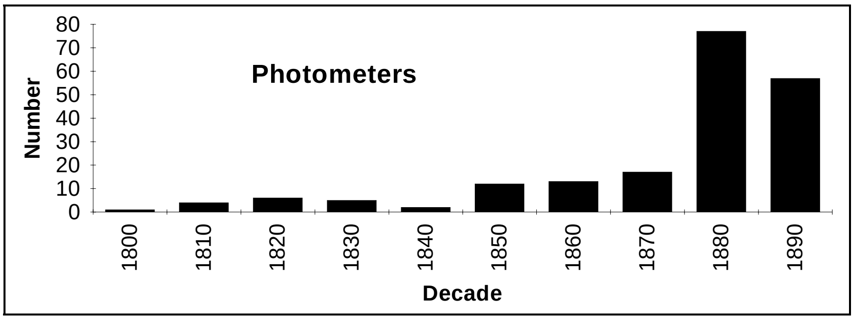


Fig. 24 Publications listed in Royal Society Catalogue category 3010.

This bibliometric analysis is, of course, subject to distortion and quantitative error. In particular, developments related to instrumentation and technique – an important part of light measurement – are likely to be under-represented, as discussed by Els *et al.*[795]

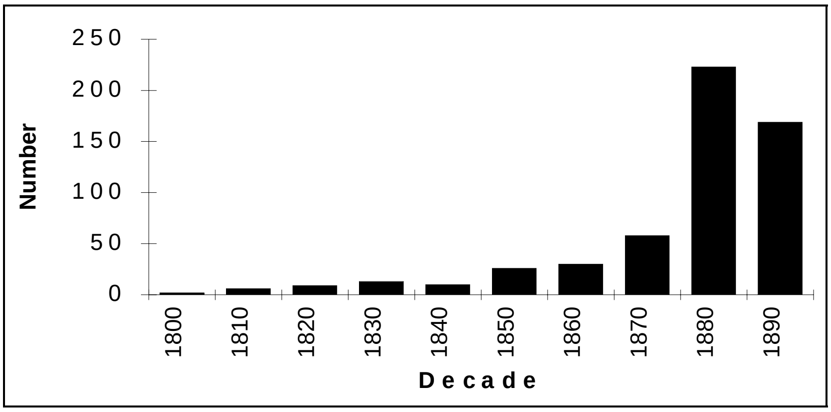


Fig. 25 Publications in all subcategories related to light measurement.

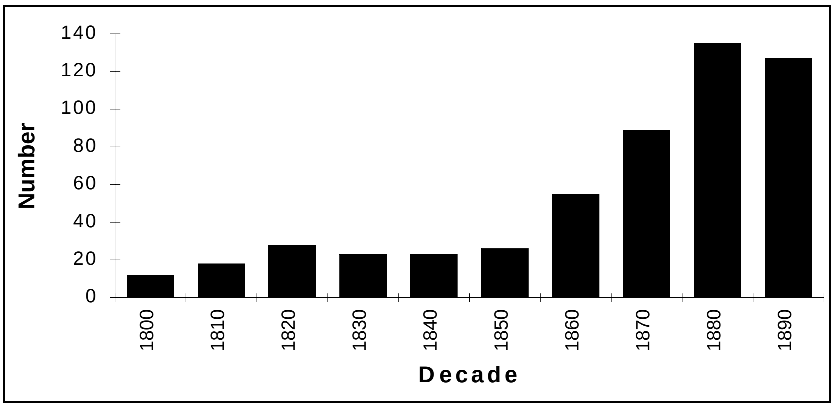


Fig. 26 Publications on 'Mass & Density' in Royal Society Catalogue category 0810.

[795]W. P. van Els, C. N. M. Jansz and C. le Pair, 'The citation gap between printed and instrumental output of technological research: the case of the electron microscope', *Scientometrics* 17 (1989), 415.

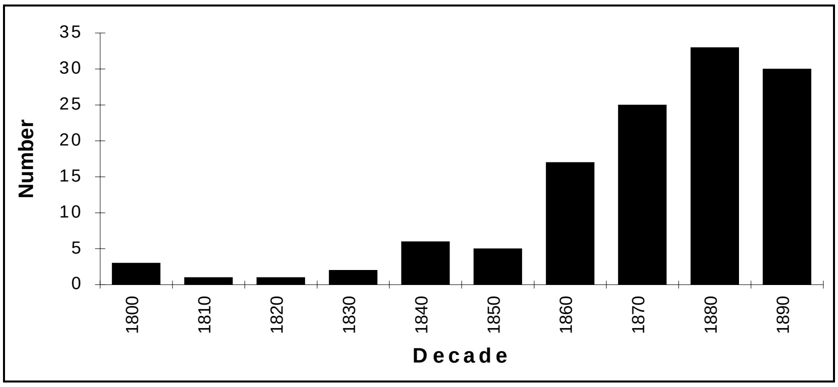


Fig. 27 Publications on ‘Gravitation’ in Royal Society Catalogue category 0700.

Appendix II
Publications on Photometry to the Second World War

As an extension to the data in Appendix I, two general indices of scientific papers, *The International Catalogue of Scientific Literature* and *Science Abstracts*, were compared to infer trends in publication in the twentieth century. For the *International Catalogue*, entries under category 3010 (photometry, units of light, and brightness) were counted for the years 1901-14.[796] This category had been indexed similarly to the same category in its predecessor publication *The Royal Society Catalogue of Scientific Papers 1800-1900*, but was not divided into subcategories. Fig. 28 is thus a continuation of the data in Fig. 25. For comparison, the number of papers published in the decade 1901-1909 is 478, indicating a doubling over the preceding decade. For *Science Abstracts*, publications in the categories *Photometry* and *Photoelectricity* were counted for the years 1898 - 1939.[797] The overlap with the former index was imperfect: the entries for *photometry* excluded the separately indexed categories *spectrophotometry*, *photometers*, and *industrial and practical applications*. Nor was there any explicit category for *photoelectricity* before 1923.

The data cannot be compared or interpreted in detail owing to the likely fluctuations caused by the different indexers and subject definitions employed over the period. However, the qualitative agreement between the *Science Abstracts* and *International Catalogue* data, illustrated by Fig. 28, indicates a significant decline in publications from the period 1905-07 until the early 1920s.[798] Fig. 29, plotting the publications in ‘photometry’ and ‘photoelectricity’ suggests that the subsequent faster

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[796]Vols. 1 to 14 of *The International Catalogue of Scientific Literature: Physics*. Data unavailable for 1915-39.

[797]Vols. 1 to 41 of the *Physics Abstracts* Subject Index.

[798]There is reasonably good statistical correlation between the number of papers in the two indexes *vs.* time. The two are rougly proportional for the 14 years examined, with the *International Catalogue* listing approximately three times as many papers as *Science Abstracts*. The least-squares fitting equation is: (International Abstracts publications) = 2.94*(Science Abstracts publications)+4.70, with a standard deviation of 19.8.

growth of the subject is correlated with the commercial development of photoelectric cells in the early 1920s.[799]

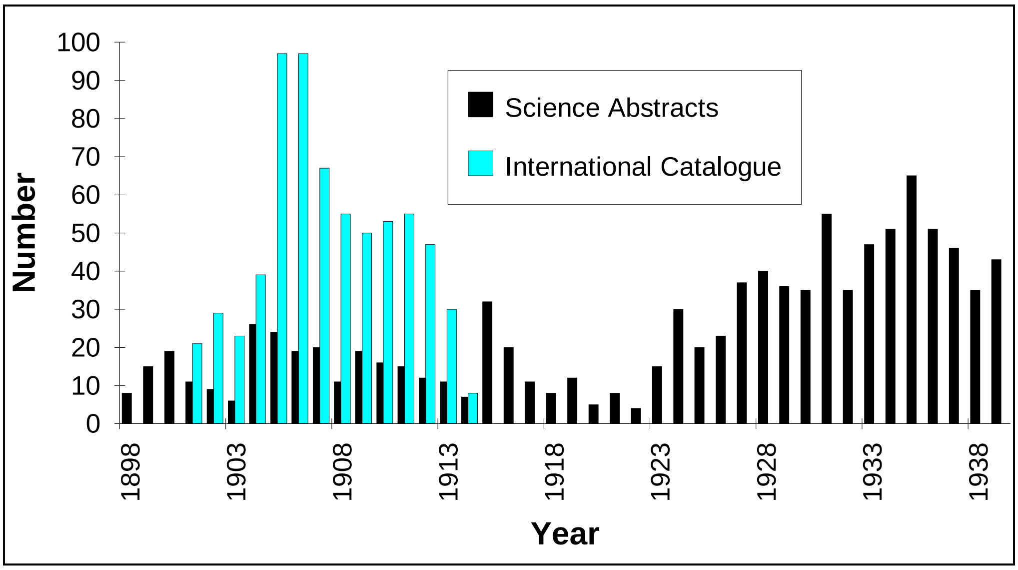

Fig. 28 Comparison of *Science Abstracts* and *International Catalogue of Scientific Literature* (Vol. 1-14) entries under the categories 'Photometry' and 3010 (photometry, units of light, and brightness), respectively.

[799]The correlation between these two subjects is not as simple as that between the *photometry* listings for the two indexes. The publication rate for *photoelectricity* increased more rapidly than for *photometry* in the early 1930s, suggesting that the former was a more active area of research.

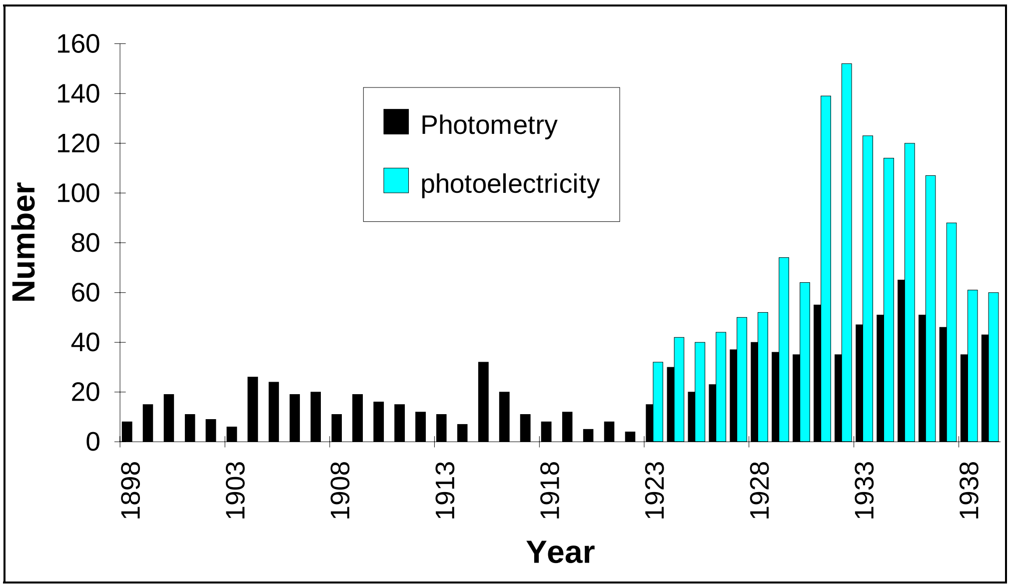

Fig. 29 Entries in *Science Abstracts* under the categories ‘Photometry’ and ‘Photoelectricity’.

Appendix III

Publications on Light Measurement in *The Journal of the Optical Society of America*

The content analysis of a single journal can illustrate shifts of interest among its authors. The publication having the largest readership, widest subject range related to light measurement and the longest continuous period of publication is *The Journal of the Optical Society of America*. The publication rate of light-measurement subjects in *JOSA* between its founding in 1917 and 1950 was found from the Cumulative Index.[800] The number of publications in five-year periods was plotted for the three categories *radiometry*, *colorimetry* and *photometry* as shown in Fig. 30.

Photometry shows no marked trend over this period, but publications in radiometry peaked during the 1920s, and those in colorimetry were high through the 1920s and 1930s. All three subjects showed higher publication rates after the Second World War.

Fig. 30 Publications by subject in the *Journal of the Optical Society of America*

[800]Optical Society of America, *Cumulative Index of the Journal of the Optical Society of America 1917-1950* (Washington D.C., 1950).

Appendix IV
Early Memberships of the Illuminating Engineering Societies of New York and London

A number of features emerge from an examination of the founding memberships of illuminating engineering societies, which were instrumental in promoting the measurement of light intensity. The charter members of the IES of New York – those joining within the first three months of its official formation in January, 1906 – and the first membership list of the IES of London for late 1909 were published in early issues of their journals.[801] The memberships were 185 and 153, respectively. Six persons were members of both societies.

Figs. 31 and 33 summarise the members by occupation. The distributions are markedly different for the two societies, even when taking account of the large fraction providing no information to the IES (NY). In America, engineers as a group comprise about 12% (31% of the listed occupations), and scientists are rare: only one chemist is listed (as 'engineer and chemist'), and no physicists. A mere four per cent use the title of Doctor or Professor. In Britain, in contrast, engineers make up more than a third of members (40%). Nine scientists are listed, and persons using the title Doctor or Professor comprise nearly one-quarter of the membership. Fully thirty per cent of the British society's members reside outside Britain (mainly in Germany, America and France), suggesting its greater international character.

Other categories of occupation display greater similarity for the two societies. About one in eight American members, and one in six British members, is listed as a manager, superintendent or company president. Interestingly, self-professed illuminating or lighting engineers make up only 5% of the membership in America and 2% in Britain. This accords with the minutes of the founding meetings, which emphasise the non-professional consensus of the members. The importance of

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[801]Source of data: S. G. Hibben, 'The Society's first year', *Illuminating Engineering (USA)* (Jan., 1956), 145-52, and Anon., 'List of officers and members, November 1909', *Illum. Eng.* 2 (1909), 829-37.

journalists in supporting the illuminating engineering movement is suggested by the significant numbers in both societies: 7 in the New York society and 6 in London.

Figs. 32 and 34 summarise the members by industrial affiliation. In America, of the identifiable company activities, slightly more than one-third of members are part of the electrical industry, and one-tenth are part of the gas industry. Five companies appear prominently as employers: the Edison company (22 IES members), General Electric (13 members), Nernst (8 members), Westinghouse (7 members) and Holophane (6 members), all but the latter of which were electrical manufacturers. In Britain, the gas and electric industries are more evenly balanced, and members from educational institutions represent a significant fraction.

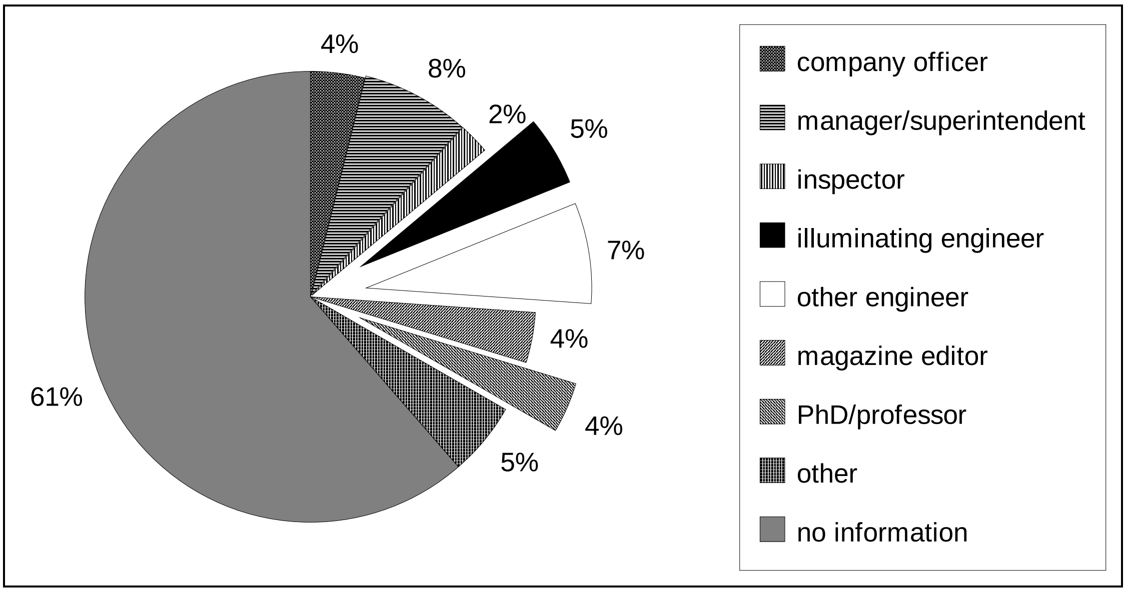

Fig. 31 Charter membership by occupation in the Illuminating Engineering Society of New York

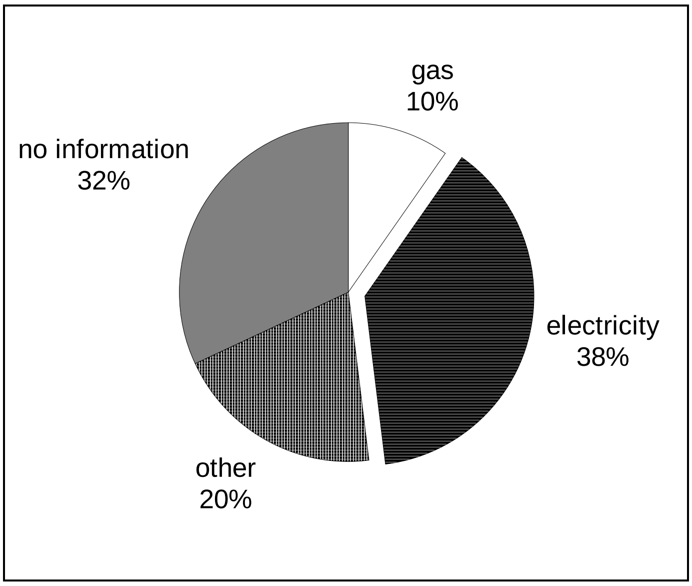

Fig. 32 IES (N.Y.) charter membership by industrial affiliation

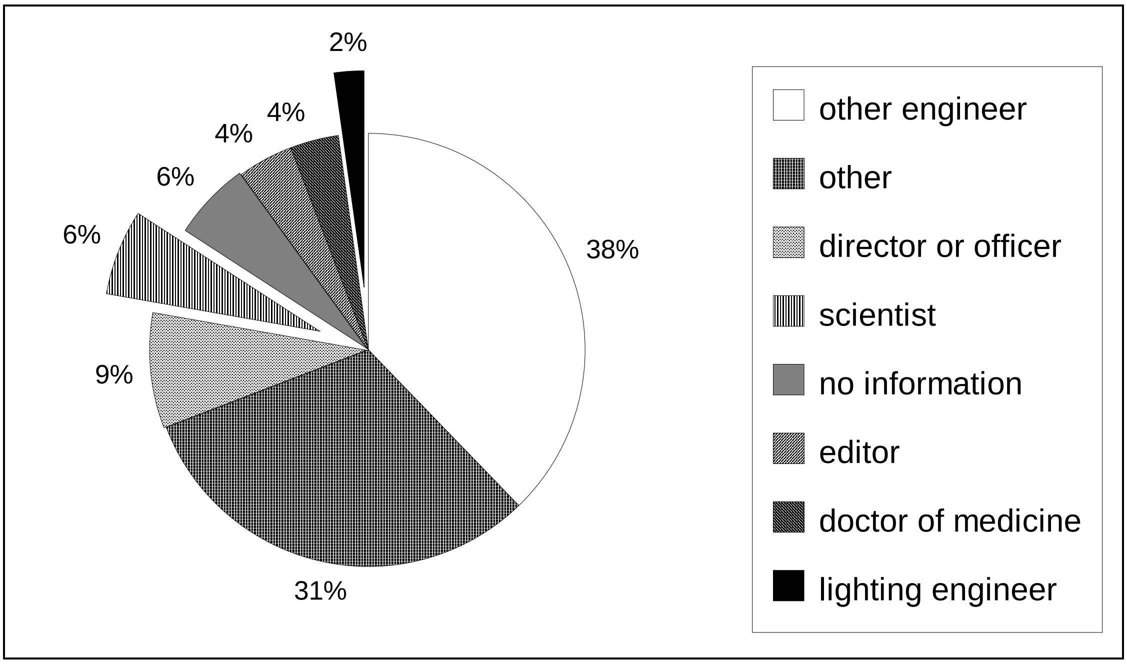

Fig. 33 Original membership by occupation in the Illuminating Engineering Society of London

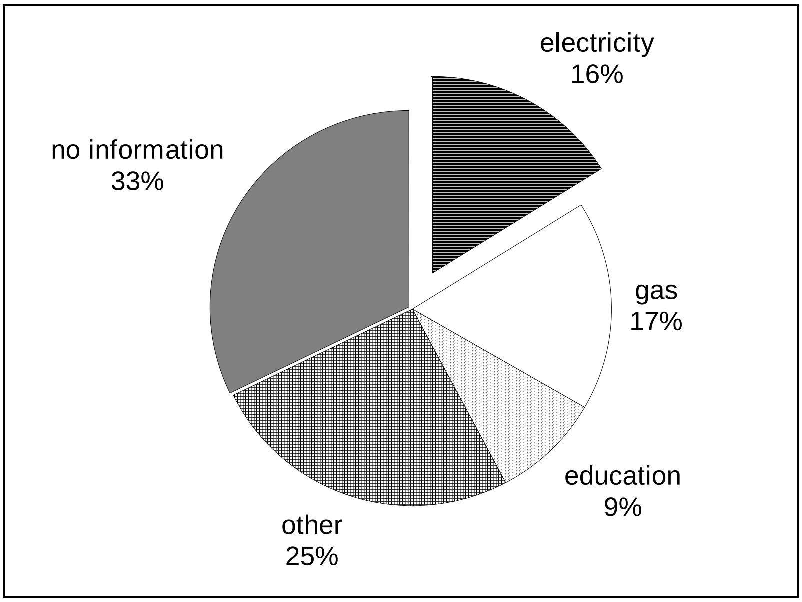

Fig. 34 IES (London) original membership by industrial affiliation

Appendix V
Matrix of organisations and individuals influential in photometry in Britain during the early twentieth century

	William de W. Abney (1843-1920)	**Leon Gaster (1852-1928)**	**Alexander P. Trotter (1857-193?)**	**Clifford C. Paterson (1879-1948)**	**John W. T. Walsh (1891-1962)**
Royal Photographic Society	President 1892-1905				
National Physical Laboratory 1899-			Donated apparatus 1903	Assistant 1903-1907; Principal Assistant 1908-1919	Junior Assistant 1913-1916; Assistant 1916-1919; Senior Ass't 1919-1955
Commission Internationale de Photométrie 1903-1913				Delegate	
National Illumination Committee 1903-		Member	Member	Member	Member
Illuminating Engineering Society 1909-		Founded Society 1909; Honorary Secretary 1909-1928	Founding member; President 1917-1919	President 1927-1928	Vice President 1926-1927; President 1929-30 and 1947-48
Commission Internationale de l'Éclairage 1913-		Proposed formation, 1913; Delegate 1921-1928	Delegate 1921-1931	Co-wrote constitution; Treasurer 1913-1949; Secretary 1913-1927; President 1927-1931	Executive Secretary 1913-1931; Vice President 1948-1955; President 1955-1959

General Electric Company Research Lab 1919-				Research Director, 1919-1949	Collaborated with staff on photoelectric photometry
Department of Scientific and Industrial Research Illuminating Committee 1923-		Member	Member	Chairman	Member

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