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Making light work: practices and practitioners of photometry

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> 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 problem.
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> (A. Guillemin, Les Phénomènes de la Physique, 1868)T[1]

Introduction

The complaint of textbook writer Amédée Guillemin was a common one in discussions of light measurement into the twentieth century. The subject was fashioned into a common scientific and sociotechnical practice in his time. A contentious human-centred activity before World War I, it was recast during the inter-war period as a symbol (for a time, at least) of precision, automation and modernity. But in contrast to the practice, which evinced a clear winnowing of techniques by the Second World War, the practitioners contributing to it did not coalesce into a well-defined community. How and why did the pursuit of light measurement come to occupy the mundane, unspecialised place that it did?

Light measurement, a hybrid subject straddling science and technology, was shaped by, and in turn shaped, its cultural environment and disparate communities of investigators.[2] This 'orphan' subject, while not the 'success story' commonly singled out for historical analysis, had developmental features that may be common to other twentieth-century subjects.[3] Part of the historiographical interest of such hybrid subjects lies in their potential for clarifying definitions and practices of science.[4]

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Emergence of subject and practice

This paper concentrates on the permutations of photometry as a communal practice, principally from the mid-nineteenth century. While earlier interest in the measurement or comparison of light intensities was sporadic, seventeenth and eighteenth century investigators characterised their new subject in durable, if inconsistent, ways.[5]

Firstly, differing claims of its feasibility and value were put in play. For some, the judgement of light intensity was perceived as a straightforward task susceptible to trivially simple methods and analysis.[6] The eye was depicted as an unproblematic and reliable detector of brightness. Their critics, on the other hand, portrayed photometry as a potentially misleading subject requiring meticulous experimental protocols and analysis.[7] This dichotomy is, of course, misleading, as there was a third, implicitly held majority view, namely that the intensity of light did not constitute a 'law-abiding' quantity meriting 'study' at all.[8]

Secondly, the style of engagement was highly individualistic. Investigators employed techniques of comparison that included variously sighting-tubes, shadow-casting, stacked absorbing glass plates, or the legibility of printed text.[9] And the purpose of photometry was defined alternately as a disinterested extension of mathematical analysis or a pragmatic means of fact-finding.[10]

"Liable to peculiar uncertainty", or "capable of accurate measurement"?[11]

This heterogeneous mixture of motivations and method continued into the nineteenth century. William Henry Fox Talbot, writing in 1832, observed that no method had been universally accepted, but that "a convenient and accurate instrument for photometrical purposes will ultimately be overcome".[12] A handful of others unproblematically devised their own solutions: for instance, Augustin Fresnel, for lighthouse design[13]; Robert Bunsen, for studies of the chemical action of light[14]; and George Biddell Airy, for solar eclipse studies[15].

But the inadequacy of the techniques of light measurement remained a dominant perception. The case of early photography provides an illustration. Even Fox Talbot never applied his photometric methods to his seminal photographic research. Indeed, for early photographers, light measurement was often a solution in search of a problem. Quantitative questions important to subsequent generations (e.g. how much light was needed to darken a photographic plate? How much do different colours of light affect the exposure? How much does an optical filter reduce the intensity?) were largely irrelevant. A correctly exposed plate was the goal of the photographer, and light intensity was merely one of the largely uncontrollable factors that affected the result. One practitioner warned:

> 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. . .[16]

Exposure time proved considerably easier to control than light intensity, and the two could largely be traded off.[17] Moreover, photographic processing using 'restraining' or 'strengthening' developers could compensate for gross errors in plate exposure. The occasional forays into light measurement by photographers were seldom appreciated by their contemporaries. The reviewer of a new commercially available photometer objected that, "the actinic or photographic energy is by no means always proportionate to its intensity", citing as example the trebled exposure required on days when the sky had a faint yellow caste.[18] Early photographers successfully avoided the 'problem' of quantitative measurement of light or recast it in terms of other variables.

Communities of light measurers, 1860-1900

Despite such indifference, photometry as a subject gained increasing interest through the second half of the nineteenth century.[19] This increased popularity resulted more from a changed perception of its utility than from an elaboration of technique. Two immiscible communities marshalled the subject into redefined roles: astronomers and gas inspectors.

Astrophysics and stellar photometry

In the opening years of the nineteenth century, the measurement of stellar magnitude had fleetingly achieved a purpose when William Herschel related the brightness of a star to its distance from the earth.[20] His work was, however, seen as simplistic by many contemporaries, undoubtedly colouring their attitudes towards the credibility of photometry. Interest in rationalising the inconsistent scale of intensity nevertheless persisted. A mid-century astronomer illustrated the imprecision surrounding the visual estimation of stellar magnitude by listing stars for which magnitudes had been reported as anything from 5.3 to 8.5, corresponding to a discrepancy of about eight times in intensity.[21] Similar concerns, accompanied by a confidence in comparative observations, led to a programme of stellar photometry at Harvard College Observatory by its first director, William C. Bond (1789-1859). Bond applied photographic methods to photometry, correlating the diameter of the stellar image with brightness. His successor, Edward C. Pickering (1846-1919), extended this limited programme into a life's work.

Pickering introduced several innovations to convert photometry from a volatile to a stable subject. Firstly, by adopting a proposed scale of magnitude and choosing a reference star against which all others would be compared, he defined a photometric scale that other workers found straightforward to accept.[22] Secondly, Pickering established what was commonly viewed as a reliable technique, devising new types of visual photometer adapted for telescopic use. His 'meridian photometer' compared an image of Polaris with the target star.

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 four thousand stars. By 1908, Pickering and his co-workers had extended the work tenfold, cataloguing 45,000 stars of the north and south hemispheres in their Revised Harvard Photometry,[23] Pickering alone recording some 1.4 million observations.[24] 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.

Aside from 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.[25] Zöllner marshalled technique and training to extend the influence of stellar photometry as Pickering did in America. His 'astrophotometer', which incorporated a petroleum-burning reference lamp, was adopted by other German observers. Established in 1877, the Potsdam Observatory became a centre for photometric observations and produced a line of researchers.[26]

By the beginning of the twentieth century, 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 growth of 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.

Growth of a social dimension

Despite this growing popularity among a small band of astronomers, photometry had remained an intensely personal affair. The apparatus had to be designed and calibrated by each investigator, the observations were performed in a darkened room or at a telescope eyepiece, and the results relied solely on the evidence of the observer's eyes. Communication of results demanded, however, that intensity calibrations be regularised. The socialisation of the subject relied upon standards.

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".[27] Even with such careful photometric methods, though, astronomers felt compelled to emphasise that they still "found it by no means easy to get good concordant observations".[28] The brightness of fluctuating light sources such as twinkling stars in variable sky conditions was difficult to measure by relatively slow visual observations.

Parkhurst used 'standard stars' 'well fixed' by other observers to enrol the support of an ill-defined community. Stellar catalogues served a social role in forming that community. But the difficulty of 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 more practical problems. If photometry was to be rendered an acceptable tool, reasoned some practitioners, generally available standards of light measurement and intensity were required.

Enculturation of standards

Standards of light intensity 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.

The illuminating gas industry, originating in England in the early decades of the nineteenth century, provided the dominant source of domestic and public lighting in most cities within two decades.[29] The London Metropolitan Board of Works (MBW) was given extensive powers to supervise the industry in the early 1860s when the number of companies proliferated, and appointed its first gas examiner in 1869.[30] The legal requirements created a new community of photometrists. The most numerous photometric practitioners, between at least 1860 and 1880, were the gas examiners of London and certain other gas-supplied cities.[31]

The first Superintending Gas Examiner, William Joseph Dibdin (1850-1925), investigated thoroughly the available photometric methods and published one of the first widely available books summarising the subject.[32] Observing that "the present chaotic condition of the Photometer itself is a fruitful source of much uncertainty", he sought to give "a full narration of the various systems now before the public".[33] 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, his organisation thus became the de facto arbiter of photometric standards in England.

By the end of the nineteenth century, engineers and scientists concerned with photometry agreed on its usefulness but bemoaned its lack of coherency, particularly for standards. 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.[34] The adjudication of the ‘best’ reference light source was a socio-political decision as much as a technical one. The setters of standards recognised early on that the intensity of flame-based lamps 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 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 evaluation of the new electric lamps and the more difficult inter-comparison of gas and electric sources, however, this argument appeared 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 contentious; flavoured by industrial allegiances, it favoured the then-dominant illuminant, gas.[35]

By 1909, the working standards in use in Britain, America and France were rationalised into an international unit based on incandescent lamps. The German-speaking countries retained the amyl-acetate burning Hefner lamp, which was, however, calibrated with respect to the international standard.[36] Here again, different (national) communities disputed the qualities that were essential to an intensity standard; definitions of replicability were particularly contentious. 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. Indeed, standards comparisons proved impossible over two successive British winters owing to high humidity.[37] 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 calibrated individually 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.

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.

Despite this lack of concord, engineers at the local scale employed photometry unproblematically to provide routine information for specific tasks.[38] 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 reference source was a “standard gas mantle, perfectly adjusted to normal luminous intensity”.[39] 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.

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.[40] An indication of the rapid trend towards 'electrotechnical photometry' is given by the laboratories set up for the judging of experiments at successive Electrical Exhibitions. In the 1882 exhibition at Munich, the photometric laboratory used numerous intermediate gas-burner standards. The following year, with competition between gas and electric lighting on the ascendant, the Vienna Exhibition did away with these in favour of electric lamps.[41] In common with the previous examples, the choice of intensity standard in these cases had other than a purely technical motive – but now the electric lamp, not gas, was in control.

The institutionalisation of photometry

The opening decades of the twentieth century were a time of rapid transition in light measurement. The emphasis of utilitarian photometry shifted from routine gas testing to the measurement of electric lamp intensities and illumination.

The setting for these changes was a new environment of research and standardising laboratories. 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".[42] Photometry was elaborated and systematised on an unprecedented scale at new institutions such as the Physikalisch-Technische Reichsanstalt in Germany (1887), the National Physical Laboratory in England (1899) and the National Bureau of Standards in the USA (1901). These bodies 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.

Photometric work at 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.[43] Another motivation was the concern raised by the financing of lighting 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.[44] The power to control and to dramatically alter lighting was accompanied by expensive decisions, raising questions concerning the relative efficiency and cost of lighting systems. 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 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 a standard based on molten platinum.[45] Textbooks, engineers and scientists echoed this universal expectation.[46] Moreover, German investigators such as the physicist 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 the 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 British consulting engineer Alexander Trotter.[47] In practice, the British and American laboratories found their funding inadequate for extensive scientific research, and relegated 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.[48] The NPL researches were motivated increasingly by projects for government departments, particularly those relating to lighting engineering.[49] The PTR turned away from both these trends, declining in international visibility during this period owing to an increased emphasis on routine and test work.

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.'[50] All three photometric laboratories gradually approached an unplanned existence mediated by special requests from industry, growing routine work and increasing responsibilities for administering legal standards.

Industrial laboratories

Research into photometry and illumination was not restricted to government laboratories, even if it initially was concentrated there. The founding of research laboratories, both governmental and industrial, was a distinctive feature of the early twentieth century.[51]

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".[52] The most relevant example is provided by the research laboratory created in 1908 for the National Electric Lamp Association.[53]

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 his version of photometry 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".[54] The laboratory also undertook an educational role by organising short courses on illuminating engineering, leading to its identification as "the university of light".[55]

Hybrid representations

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 contributed to its splintering into specialties.[56] 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. But they found it difficult to compartmentalise the field into radiometric, photometric and colorimetric components. Even with increasingly organised research, practical light measurement proved elusive and, warned some, illusory. The illuminating engineers, astronomers and institutionalised researchers remained separated by technological problems.

Technology in transition

The inter-war period marked a sea-change in the direction and scope of photometry. Until then, the subject was driven not by technological innovations but by cultural imperatives. Engineering practice, centring on visual methods, remained little changed from the 1870s until the 1920s for the vast majority of photometric work.[57] By the Great War, however, astronomers and spectroscopists were increasingly adopting physical methods of light measurement, based principally on photography. By the late 1920s, though, all practitioners began to employ photoelectric measurement techniques and practice again coalesced to a single technique. The 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 'objective' physical techniques. This gradual process, repeated in each community, involved the recasting of photometry into seemingly 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 stabilisation of visual photometry

As routine uses of photometry such as lamp standardisation and testing became commonplace after 1900, visual photometry became highly systematised, serving as the sole method employed at the national and industrial laboratories involved with photometry.[58] This is not to say that these laboratories shunned physical techniques; rather, they defined their task as one of determining brightness as perceived by the human eye. 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 furnish merely "a development of our powers".[59] This central role of the eye in photometry was accepted by physicists as much as by pragmatic engineers. The PTR physicists Otto Lummer and Eugen Brodhun, inventors of the most popular visual photometer, declared:

> 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.[60]

But the usages of photometry proliferating by the turn of the century were accompanied by criticism from their users and ever more vocal cautions from experts concerning the complications of visual observation. The experimental protocols were increasingly accompanied by warnings from experienced practitioners. "Photometry is not a simple and well-defined subject", wrote one author,

> 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.[61]

The limited range of brightness over which the eye could precisely match two lights was also increasingly noted; and too little or too much mental concentration was undesirable. Another commentator added to the lengthening list of observational constraints:

> Looking at the photometer screen for too short a time reduces the precision, but this happens also if the period is made too long. . . 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.[62]

A worryingly 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 obtained by the other".[63] Taking into account these various factors, an unfatigued and unbiased observer, using comfortable 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.

Because the intrinsic reliability of human observers was seen as 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 by restricting measurement to highly controlled circumstances. If the observer was to be a mandatory component of the apparatus, they reasoned, then the eye must be rendered as reliable as the rails, cranks and standard lamps that shared the room.

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. 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.[64] By constructing a growing list of 'perturbing effects' which caused deviations from the ideal 'linearity' and by limiting the scope of measurements, quantification was thus made to appear increasingly plausible and, indeed, natural.

Such systematisation of observation could make an onerous task practicable. By 1908, an engineer 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.[65]

Standardisation provided the efficiency and high-volume measurements required by industry. The process was rendered routine and rapid despite 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, 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.[66]

The standardisation of visual photometry arguably reached its zenith in the establishment of a British Standards Specification for Portable Photometers in 1925.[67]

Expectations of physical photometry

Visual methods, increasingly accepted as workable, nevertheless attracted the criticism of being slow and elaborate. Physical methods came to embody a different set of expectations. 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, replicability and convenience – indeed, this is the conventional 'technological determinism' often propounded by technical histories.[68] There was, however, 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 seldom is simple, and frequently has a significant cultural component.[69] Thus, while espousing rational arguments for a physical detector of light, its proponents weighted their views with tacit considerations.

By the turn of the century, nearly all photometric 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 technical community. Four principal motivations can, however, be discerned for the adoption of physical methods, namely assessments 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 for at least two reasons. First, human observations were increasingly labelled as unreliable; second, practitioners were placing greater emphasis on relating the perceptual property of intensity to the physical quantity of energy.[70]

'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.[71] 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".[72] 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 merely a good approximation for what they sought; and third, that a physical detector was necessarily better at attaining astronomers' physical objectives of measurement.

A 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' became a fashionable analogy to the '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.[73]

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 lighting engineers – was discarded in favour of a practical search for superior detectors.

ii) precision

For the researchers at the government standards laboratories, the potential repeatability of physical methods was stated as their chief advantage. John Walsh, responsible for the NPL Photometry Division between the wars, secretary of the 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.[74]

Walsh explicitly linked improved precision, physical photometry and scientific progress – a progress that he saw as having been impeded by visual methods.

iii) speed

The urgency for rapid and de-skilled photometry rose as applications such as light bulb manufacture grew. Drawing an analogy with the popular Kodak cameras, the editor of The Electrician acclaimed 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.[75]

iv) automation

Closely allied to a desire for speed was a desire for the automation of photometric measurements, part of a trend towards automatic control in engineering and industry.[76] 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 visual observers.

Automation symbolically removed the problematic observer from the measurement, an attractive and highly visible benefit of physical methods. By relegating the operator to the interpretation of 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.

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 problematic observer altogether. Along with these practical advantages, though, physical photometry required a change of philosophy. The 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 framing light measurement in this way, they reclassified the eye as merely an unreliable detector of radiant energy, rather than as the central element in a perception-oriented technique. The successful tailoring of photometry to the conceptions of physical scientists was to make it the dominant view.

The replacement of visual by photographic methods

The transformation of photometry from human to 'physical' form occupied the first third of the twentieth century. By the turn of the century, despite the evolutionary improvements in visual photometers and observational techniques, photographic photometry was making inroads among astronomers. It had unique advantages. The Royal Engineer and educator William Abney, who was a prolific experimenter in both vision and photographic studies, predicted in 1893 that "note-book records of photometric work would soon become obsolete, and that photographic records would become general".[77] A photograph could, for example, record an intensity for later examination and matching by eye. This capability 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.[78] The analytic convenience of evaluating 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.[79] By the first decade of the twentieth century, visual observations for stellar photometry had been effectively superseded.

From the astrophysics community, photographic photometry spread to laboratory spectroscopists, who found that the ability of the photographic plate to integrate a faint spectral image made it practicable where the human eye was not.[80] Moreover, the photographic plate averaged the irregular intensities produced by the flame or arc sources that were used for vaporising materials in spectral analysis. Photography also extended and refined observational range. First, when measuring the relative brightness of different portions of a spectrum when the light source is fluctuating, it provided a method of simultaneously recording all wavelengths. Second, it could reveal the short ultraviolet and long infrared wavelengths to which the eye is blind.[81]

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.[82] 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 record weak images and to analyse permanent records.

Despite astronomers' unproblematic exploitation of the seemingly straightforward analogy between visual and photographic methods of photometry, photographic photometry made no inroads into industrial applications. 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 engineering work, the process of exposure, processing and subsequent examination of the plates by eye was pointlessly circuitous. Moreover, the photographic method required standardised photosensitive materials and processing which introduced even more sources of error into the photometric evaluation. By World War I, then, engineers were becoming separated from scientists by technique as well as by motivations. Indeed, the use of photographic in preference to visual methods serves as a reasonable criterion for categorising engineering and scientific uses.

The adoption of photoelectric photometry

The publicising of the light-sensitive electrical properties of selenium in the 1870s made relatively little impact on photometric technique.[83] By the 1890s, however, a few astronomers were experimenting with photoelectric devices, and heat-sensitive detectors such as thermopiles and bolometers. The astronomical and electrotechnical communities were dealing with different domains of light measurement. Astronomers measured dim and angularly small 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 relatively bright, large-area lamps. They demanded more precise measurements for comparing the technical performance and manufacturing tolerance 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 in their limited inter-communication. Most importantly, physical methods were rejected because they were seen as working poorly in practice. One illuminating engineer rejected 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’.[84] Only with the inclination provided by a despair of visual methods and faith in the unsubstantiated promise of photoelectric technology would a practitioner persevere.

Almost ignored by astronomers, the <u>conceptual</u> problem of adequately replacing the eye by an equivalent physical detector was broached by other technical communities. By the second decade of the century, the conjunction of a thermopile and a filter to screen out invisible radiation was being touted by physicist Harold Ives as an ‘artificial eye’.[85] The central problem was to transform the spectral response of the radiometer (which responded almost equally to wavelengths well beyond the visible range) into a close approximation of the very uneven colour response of the human eye. Practical problems centred on the feeble response of such a system to visible light. “The degree of sensibility required is very high”, admitted Ives, and hence the applicability of refined thermopile and galvanometer designs was severely limited.[86]

Where the selenium cell was a unique fluke – an unexpected discovery – the photoelectric cell was based solidly on the photoelectric effect, which had been studied intensively from the first decade of the century. Moreover, the characteristics of selenium were touted as complex and insoluble, depending on its purity, manner of preparation, type of electrical contacts, and past exposure to light,[87] while the properties of ‘photoelectric’ devices promised to be decipherable. Norman Campbell, designing photocells at GEC in the 1920s, contrasted them both socially and technically with the earlier selenium devices:

> 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.[88]

Yet for straightforward photometry, investigators at the NPL (collaborating with GEC in the early 1920s) found the photocells to be "no improvement" on the visual method, and definitely "more troublesome". 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. Second, as astronomers had discovered two decades earlier, the photoelectric signal was small, requiring a sensitive (and delicate) electrometer to measure the emitted current. Attaining the necessary sensitivity and stability was difficult.[89] Third, the photocells did not produce a signal proportional to the intensity of light; their response varied dramatically with 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. 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, emphasising "establishing a scientifically accurate system of photo-electric photometry <u>in spite</u> of deficiencies of stability".[90] They reported that "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".[91] Using these strategies, the photometrist had been translated from meticulous observer to meticulous instrument minder. 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.

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. In a process that began with a fashion for quantitative measurement, photometry was rendered culturally stable by the emergence of commercial applications.

Commercial development

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 measurement to new applications demanding the development of new kinds of measuring equipment. Employing this new apparatus, scientists having had no previous concern with photometry were able to apply the method to their particular problems. The expansion of commercial light measurement thus involved the extension of the network of 'actors' to several new types operating at different levels.

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 contemporary analysts to be too fragile for industrial use. Nevertheless, GEC in the UK and Westinghouse in the USA targeted this market by constructing demonstration devices as diverse as photoelectric newspaper bundle counters and automatic door openers.[92] By the mid-1930s a British plant engineer could report with satisfaction that "many miles of street lighting" were controlled by light-actuated switches, and that "most of the large power stations" employed photoelectric smoke detectors.[93]

The second, and more financially significant, stage of commercialisation was made with 'flat plate' photocells. Some five years after the commercial introduction of photoelectric tubes, instrument manufacturers began to market portable instruments employing improved variants of the selenium cell. 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.[94] Similar cells marketed by a variety of manufacturers made practicable a variety of products owing to their small size and modest electrical requirements. To differentiate their more elaborate – and expensive –

products from these flat plate cells, manufacturers of the earlier devices dubbed them 'phototubes'.

Ironically, the relatively inaccurate flat-plate sensors proved more successful than their predecessors in bringing quantification to industry. 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".[95] In 1933, the Science Museum in London recognised this technical and commercial wave by mounting a three-month exhibition of photo-electric equipment.[96]

As a direct result of such exhibits and portrayals, the trend to physical photometry grew during the following decade. By 1939, the term 'photometer' was almost universally preceded by the adjective 'photoelectric' in the titles appearing in instrument journals.[97] Practitioners clearly had come to imbue photoelectric methods with the qualities of stability, accuracy and modernity.

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".[98] 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 became available in the early thirties.[99] Moreover, the entities measured had little relevance for the general public. But the flat-plate photocells introduced in the early thirties caused photoelectric technology to diffuse widely, multiplying the number of devices and users. By the mid 1930s, simple physical photometers were popular among engineers and amateur 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.[100]

Nor were photoelectric detectors confined solely to photometry. Inventors increasingly integrated the 'simple' photocell into ever more complex products produced in larger volume and with higher profit. Even Albert Einstein co-patented an automatic exposure system for a camera.[101]

The commercialisation of light measurement 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.

'De-numerating' photometry

The increased public profile and commercial success of light measurement was not solely, or even predominantly, a technology-driven affair. Indeed, the cultural invention of a need – that of industrial matching and testing – predated reliable photoelectric detectors. Nor did the scientific consensus regarding quantification compel its industrial acceptance: the first commercial inroads were made by devices that merely <u>sensed</u> rather than <u>measured</u> light. Other cultural factors also played a role, particularly in the placing of an increased value on automation and standardisation.

Despite commercial expansion, the post-WWI 'rehabilitation' of photometry faltered by the late 1930s. Many practising engineers were reporting that 'the simplest applications of photocells are frequently the most useful ones'.[102] Quantification did not always provide solutions. By stepping back from the problematic physical quantification of light, the mundane applications of photoelectric detectors made inroads into commerce and industry where high-precision instruments had not. Discussing the automatic detection and recording of smoke levels from factories, a plant 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.[103]

Moreover, designers now warned, 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.[104] The quantification offered by the manufacturers was increasingly seen as incomplete or misleading. 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.[105]

The incorporation of colour measurement (so-called 'heterochromatic photometry') proved problematic, and led researchers at the national laboratories to a retreat towards psycho-physical analysis.[106] Physical photometry was again being remoulded. Its new definition as a modern replacement for the subjective human observer was becoming tempered by a reputation for inadequacy.

Convergence of practice

Without invoking Whiggish analysis, the multiple mutations 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 opinion regarding how light should be described and treated. As a collection of isolated communities, 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 objective of quantitative measurement of light intensity. This trend towards quantification cannot be seen as a natural progression; rather, the desire for measurement is a consequence of the adoption of particular cultural goals emphasising the comparison and standardisation of goods and services.[107] The general acceptance of quantification implicitly involved the selection of concepts deemed important, and those concepts became concensually accepted in different nations and technical communities. Thus the assurance of uniform manufactured goods and demonstrably adequate lighting were generally perceived as being more worthy of attention than, for example, a complex psycho-physical or aesthetic description of light and colour. Such standards stabilised the subject and aided consensus.

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 measurement. Hence the judgement that the photocurrent produced by illuminating a photoelectric detector 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.

Another element in the convergence of practice was the portrayal of light as a particular manifestation of electromagnetic radiation.[108] 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.[109] By the end of the decade the consolidation of practice was nearly complete: although Germany, the nineteenth-century leader, had long resisted change in standards of light intensity, it adopted a standard based on molten platinum along with France, America and Britain in the early months of the Second World War, on New Year's Day, 1940.

An 'undisciplined science'?

The growing unity of light-measurement practice did not generate a comparable merging of the disparate communities of practitioners. No single discipline or profession emerged to appropriate and control the enlarging body of expertise. The changes in the practice of light measurement during the early twentieth century can, instead, be characterised as a transition towards an increasingly co-operative 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, but continued separation, of distinct communities.

The failure to achieve autonomy was a crucial characteristic of the subject of light measurement, and one that sets it apart from more successful 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.[110] 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.

Historians have commonly postulated a connection between discipline formation and the maturity of a subject.[111] 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.[112] Law suggests that the first two of these are later stages in development than the third. Such an evolutionary path is inappropriate for photometry. 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".[113] 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'.

Nor can light measurement be relegated to mere technology or tool-making, because only 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 photographic photometry.[114]

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 undertook them. It minimises the scope of the subject and neglects its pretentions for the status of a science.[115]

Is this 'peripheral' science, finally, just another form of applied science? The primary difficulties with the term 'applied science' are twofold. First, it implicitly assumes a direction of development, i.e. scientific discovery followed by practical application. Second, it suggests an asymmetry between science, the provider, and technology, the beneficiary. Such a categorisation extends the hierarchy further by implying an inadequate or unsuccessful science. Donald Cardwell, for example, epitomises the conventional historical view 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, in part, with the statement that 'researches of the applied scientist are guided not by purely scientific considerations, but by the requirements of industry. . . this does not mean that the applied scientist and technologist are. . . truncated scientists'.[116] I suggest that this 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. The subject of light measurement, indeed, was peripheral to, and yet reliant upon, both.

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[1]A. Guillemin, Les Phénomènes de la Physique (Paris, 1868), pp. 272, 274 (my translation).

[2]Bruno Latour [We Have Never Been Modern (New York, 1993)] has recently employed the term 'hybrid' in the sense of linkages between the scientific, political, social, economic, legal, religious, and technological dimensions of 'nature-culture'. I adopt here a more limited perspective focusing on the 'science-technology' dimension, while agreeing that the other components are, in principle, relevant.

[3]The limited historical analysis of light measurement includes H. Kangro, The Early History of Planck's Radiation Law (London, 1976) for tangential aspects of German radiometry, and R. Steven Turner, In the Eye's Mind: Vision and the Helmholtz-Hering Controversy (Princeton, 1994) regarding German colorimetry. The most extensive bibliography was published by an important contributor to the subject, J. W. T. Walsh, in Photometry (London, 1926).

[4]The unfocused and untended nature of hybrid subjects may frequently prevent them from crossing what Svante Lindqvist has called the 'historiographical threshold', that level of fame that must be exceeded to attract the interest of historians. I concur with his argument that the 'middle' levels of science are worthy of attention, and that "the network itself may be more important than its nodes" ["Harry Martinson and the periphery of the atom", in: S. Lindqvist (ed.), Center on the Periphery: Historical Aspects of 20th-Century Physics (Canton, MA, 1993), ix-lv].

[5]The inverse-square law of illumination, for example, was disputed through the seventeenth century. See P. E. Ariotti & F. J. Maracolongo, "The law of illumination before Bouguer (1729): statement, restatement and demonstration", Ann. Sci. 33 (1976), 331-40. Christian Huyghens described comparative stellar and solar observations [Cosmotheoros sive de terris coelestibus earumque ornatu conjecturae (The Hague, 1698). Johann Lambert coined the term photometry in his work Photometria sive mensura et gradibus luminus, colorum et umbrae (transl. by E. Anding, Ostwald's Klassiker der exakten Wissenschaften, nos. 31, 32 and 33 (Leipzig, 1892) abridged German translation).

[6]For example, R. P. François-Marie, Nouvelles Découvertes sur la Lumière pour la Mésurer et en Compter les Degrés (Paris, 1700) and J. J. d'Ortous de Mairan, Mém. Acad. Roy. des Sci. Paris (1721), 8-17.

[7]The major treatises of Pierre Bouguer [Essai d'Optique sur la Gradation de la Lumière (Paris, 1729; transl. by W. E. Knowles Middleton, Toronto, 1961) and Traité d'Optique sur la Gradation de la Lumière (Paris, 1758)] and extensive investigations by Benjamin Thompson [e.g. "A method of measuring the comparative intensities of light emitted by luminous bodies", Phil. Trans. Roy. Soc. 84 (1794), 67-82] stressed the need to compare light sources.

[8]Quantitative intensity relationships were proposed by Bouguer, Lambert and others, but frequently there was little attempt at verification or justification. In an 1809 paper, for example, Étienne Malus, discoverer of polarisation by reflection, inferred a law of intensity as a function of polariser angle by a dubious method [J. Z. Buchwald, The Rise of the Wave Theory of Light (Chicago, 1985), 45-8].

[9]Bouguer, Thompson, François-Marie and Celsius, respectively.

[10]Lambert and Thompson, respectively.

[11]H. F. Talbot, "Experiments on light", Philosophical Magazine 5 (1834), 321-34, p. 327-8.

[12]Ibid.

[13]The design of lighthouses proved to be the primary involvement of optical scientists in photometry, other applications being appropriated by illuminating and electrical engineers.

[14]R. Bunsen & E. H. Roscoe, 'Photo-chemical researches', Philosophical Transactions of the Royal Society of London 149 (1859), 879-926. The so-called 'Bunsen grease-spot photometer' of 1843 remained the most popular device for half a century.

[15]G. B. Airy, 'Suggestions for observation of the annular eclipse of the sun, 1858, March 14-15', Monthly Notices of the Royal Astrononomical Society 18 **(**1858), nos. 4 & 5.

[16]C. R. Woods, "On latitude of exposure", Photographic News 27 (1883), 113-114.

[17]A photosensitive medium was found to integrate light, changing its optical density in rough proportion to both exposure time and intensity. Deviations from this relationship (denoted 'reciprocity failure') was explored near the end of the century.

[18]Anon., "the Simonoff photometer", Photographic News 28 (1884), 610. This visual acuity device consisted of a telescope incorporating an adjustable aperture wheel and graticule with inscribed letters. The user selected the aperture, calibrated in terms of intensity, required to make the smaller letters illegible when the telescope was pointed at the scene of interest.

[19]The Royal Society Catalogue of Scientific Papers 1800-1900 (Cambridge, 1912), which employs seven subject categories related to photometry and light intensity, lists 1 to 10 papers per decade until 1850, 30 papers in the 1860s, 58 in the 1870s, and over 200 in the 1880s and 90s.

[20]See M. A. Hoskin, William Herschel and the Construction of the Heavens (London, 1963). Herschel's interest was provoked by earlier work by John Michell ["An inquiry into the probable parallax and magnitude of the fixed stars", Phil. Trans. Roy. Soc. (1767)].

[21]W. R. Dawes, "On a photometrical method of determining the magnitude of telescopic stars", Monthly Notices of the Royal Astronomical Society 11 (1851), 187-90.

[22]Pickering appropriated the scale of N. R. Pogson (1856), which defined a magnitude as a change of intensity of $100^{1/5}$.

[23]Published as volumes 50 and 54 of Annals of the Harvard College Observatory (Harvard, 1908).

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

[25]J. Zöllner, Photometrische Untersuchungen (unpublished PhD thesis, Basel, 1859).

[26]Zöllner's student, Hermann Carl Vogel 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.

[27]J. A. Parkhurst, Researches in Stellar Astronomy During the Years 1894 to 1906 (Washington, D.C., 1906), 8.

[28]G. Liveing & J. Dewar, "On the influence of pressure on the spectra of flames", Astronomy & Astrophysics 11 (1892), 215-21.

[29]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).

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

[31]France and Germany instituted similar programmes. See, for example, P. Fleury, Étalons Photométriques (Paris, 1932).

[32]W. J. Dibdin, Practical Photometry: a Guide to the Study of the Measurement of Light (London, 1889).

[33]<u>Ibid.</u>, 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.

[34]See A. Palaz, <u>A Treatise on Industrial Photometry, With Special Application to Electric Lighting</u>, transl. by G. W. & M. R. Patterson (New York, 1894), Chap. 3.

[35]For a similar case in the enculturation of <u>electrical</u> instruments, see G. J. N. Gooday, "The morals of metering: constructing and deconstructing the precision of the Victorian electrical engineer's ammeter and voltmeter", in: M. Norton Wise, ed., <u>The Values of Precision</u> (Princeton, 1995).

[36]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.

[37]NPL <u>Report</u> (Teddington, 1913-1914), 50.

[38]For a particularly standardised measurement protocol, see J. Abady, <u>Gas Analyst's Manual</u> (London, 1902).

[39]E. Alglave & J. Boulard, <u>La Lumière Électrique: son Histoire, sa Production et son Emploi</u> (Paris, 1882), 301-4, p. 303 (my translation).

[40]The decline of routine photometric testing of gas supplies was accelerated by a trend towards the simpler technique of calorific testing, commonly adopted by 1910 [L. Gaster & J. S. Dow, <u>Modern Illuminants and Illuminating Engineering</u> (London, 1920), 72-3].

[41]A. Palaz, <u>op. cit.</u>, 181.

[42]D. Cahan, <u>An Institute for an Empire: the Physikalisch-Technische Reichsanstalt 1871-1918</u> (Cambridge, 1989), 17-8.

[43]The British 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". In America, the Illuminating Engineering Society published a lighting code in 1910, which led to regulations for factory lighting in five states. 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.

[44]Books on photometry began to emphasise the new illuminants, e.g. W. M. Stine, <u>Photometrical Measurements and Manual for the General Practice of Photometry, With Special Reference to the Photometry of Arc and Incandescent Lamps</u> (New York, 1900).

[45]For a technical history of the Violle standard, see Fleury, <u>op. cit.</u>, Chap. 4.

[46]See, for example, Alglave, <u>op. cit.</u>

[47]A. P. Trotter, <u>Illumination, Its Distribution and Measurement</u> (London, 1911), 8.

[48]Publications during the period included booklets ofsn home maintenance, budgeting and efficient purchasing.

[49]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", <u>Transactions of the Illuminating Engineering Society</u> (New York) 24 (1929), 473-86.

[50]R. Cochrane, Measures for Progress: A History of the National Bureau of Standards (Washington, D.C., 1966), 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”, Physics Today 31 (1978), 23-30.

[51]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”, Social Studies of Science 17 (1987) 479-518, and J. K. Smith, Jr., “The scientific tradition in American industrial research”, Technology & Culture 31 (1990), 121-31. For the British case, see M. Sanderson, “Research and the firm in British industry, 1919-39”, Science Studies 2 (1972), 107-51.

[52]Sanderson, ibid., 135.

[53]For an economic history, see A. A. Bright, Jr., The Electric-Lamp Industry (New York, 1949), esp. chapter 6. Other significant industrial laboratories that influenced light measurement practice were the Westinghouse Electrical and Manufacturing Co. in Pittsburgh, and the Eastman Kodak Laboratories at Rochester, set up in 1912. For the important research laboratory at Wembley, England, see R. Clayton & J. Algar, The GEC Research Laboratories 1919-1984 (London, 1989), Chap. 1. Its first director, Clifford Paterson, mirrored the case of Hyde in being tempted from his post as leader of photometry at the NPL.

[54]E. P. Hyde, “The physical laboratory of the National Electric Lamp Association”, Illum. Eng. 2 (1909), 758-61.

[55]D. F. Noble, America by Design: Science, Technology, and the Rise of Corporate Capitalism (New York, 1979), 122-123 and 171-173.

[56]This was also a general consequence of the increase in non-academic careers for physicists. Spencer Weart has described how, after WWI, the existence of national and industrial laboratories promoted a schism between ‘applied’ and ‘pure’ physics. See “The rise of ‘prostituted’ physics”, Nature 262 (1976), 13-7.

[57]Compare, for example, the texts of Walsh [op. cit, 1926] and Dibdin [op. cit, 1889].

[58]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.

[59]Trotter, op. cit. 66-67.

[60]O. Lummer & E. Brodhun, “Photometrische Untersuchungen”, Zeitschrift für Instrumentenkunde 9 (1899), 41-50 and 461-5, quoted in Hans Kangro, Early History of Planck’s Radiation Law (London, 1976), 152. The Lummer-Brodhun photometer (1889) eclipsed the Bunsen ‘grease-spot’ photometer (1843) in popularity within a year of its introduction.

[61]P. Stiles, Photometrical Measurements, quoted in Walsh, op. cit., vii.

[62]H. Bohle, Electrical Photometry and Illumination (London, 1912), 82.

[63]Walsh, op. cit., 316. This was a repetition of a procedure described by Benjamin Thompson in 1794 [Philosophical Transactions of the Royal Society of London 84 (1794), 362].

[64]“The Purkynje effect renders the photometric comparison of differently coloured lights at low intensities almost impossible” [Walsh, op.cit., 69].

[65] L. Gaster, The Illuminating Engineer 1 (1908), 794.

[66] Trotter, op. cit., 192.

[67] K. Edgcumbe, "The British Standards specification for portable photometers (No. 230/25)", The Illuminating Engineer 19 (1926), 70-1.

[68] E.g. J. W. T. Walsh, op. cit.

[69] 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", British Journal for the History of Science 27 (1994), 3-21.

[70] More accurately power density, expressed as energy per unit time per area or per solid angle.

[71] 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), 261-286.

[72] J. Stebbins, "The measurement of the light of stars with a selenium photometer, with an application to the variations of Algol", Astrophysics Journal 32 (1910), 185-214, p. 205-6 [emphasis added].

[73] 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 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", Proceedings of the Royal Society of London A80 (1907), 19-25; H. E. Ives, "Note on the least mechanical equivalent of light", Journal of the Optical Society of America 9 (1924), 635-8; and Walsh, op. cit., 296.

[74] J. W. T. Walsh, discussing N. R. Campbell & M. K. Freeth, "Variations in tungsten filament vacuum lamps: a study in photo-electric photometry" in Proceedings of the Optical Convention 2 (London, 1926), 253-74.

[75] Anon. editorial, The Electrician 56 (1906), 1037.

[76] For an analysis of the attractions of automation, see S. Bennett, ""The industrial instrument – master of industry, servant of management": automatic control in the process industries 1900-1940", Technology & Culture 32 (1991), 69-81.

[77] Anon., "Capt. Abney on photometry", The Electrician 32 (1894), 625.

[78] The application of photographic methods to astronomy was by no means straightforward, however. See, for example, H. Rothermel, "Images of the sun: Warren De la Rue, George Biddell Airy and celestial photography", British Journal for the History of Science 26 (1993), 137-69.

[79] 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.

[80]The route for this technological exchange was undoubtedly through astrophysicists, who themselves employed laboratory spectroscopy to generate comparison spectra.

[81]W. de W. Abney & E. R. Festing, "On the influence of the molecular grouping in organic bodies on their absorption in the infra-red region of the spectrum", Proceedings of the Royal Society of London 31 (1882), 416-8.

[82]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 & 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", Journal of the Optical Society of America 19 (1929), 267-307; and, G. R. Harrison, "Current advances in photographic photometry", Journal of the Optical Society of America. 24 (1934), 59-71.

[83]For example, the Siemens & Halske selenium photometer of 1875 had little commercial success.

[84]J. R. Barr & C. E. S. Phillips, "The brightness of light: its nature and measurement", The Electrician 32 (1894), 525-7, p. 525.

[85]See W. W. Coblentz, "The physical photometer in theory and practice", Journal of the Franklin Institute 180 (1915), 335-48, and H. E. Ives, "A precision artificial eye", Physical Review 6 (1915), 334-44.

[86]Ives, ibid., 335.

[87]See C. A. Hempstead, Semiconductors 1833-1919: An Historical Study of Selenium and Some Related Materials (PhD thesis, Univ. Durham, 1977), 100-5.

[88]N. Campbell & D. Ritchie, Photoelectric Cells – Their Properties, Use and Applications (London, 1929), v.

[89]NPL Report (Teddington, 1925), 123.

[90]See N. R. Campbell, "Photo-electric colour-matching", Journal of Scientific Instruments 2 (1925), 177-87.

[91]NPL Report (Teddington, 1927), 128.

[92]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, c1932).

[93]C. H. Dobell, Transactions of the Illuminating Engineering Society 1 (1936), 143.

[94]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", Review of Scientific Instruments 4 (1933), 83-5, or G. A. Shook & B. J. Scrivener, "The Weston Photronic cell in optical measurements", Review of Scientific Instruments 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.

[95]Anon., "Clarity tester for gelatine", Nature 137 (1936), 861.

[96]Anon., "Exhibition of photo-electric equipment", The Illuminating Engineer 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.

[97]A standard for flat-plate photoelectric cells was written during this period: British Standard Specification for Photo-electric Cells No. 586-1935.

[98]S. R. Weart, op. cit., 14.

[99]E.g. Lance, op. cit (ref. 92).

[100]C. A. Atherton, "Comité d'études sur la pratique de l'éclairage", Compte Rendu de la Commission Internationale de l'Éclairage (London, 1935), 653.

[101]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].

[102]R. C. Walker, "Some applications of light-sensitive cells", Transactions of the Illuminating Engineering Society 1 (1936), 129-34, p. 132.

[103]Ibid, 132-3.

[104]S. English, "Some properties of the cells used in Holophane-Edgcumbe Autophotometers", The Illuminating Engineer 21 (1935), 94-6.

[105]K. Gibson, "Progress in illumination", The Illuminating Engineer 21 (1930), 265-72, p. 271.

[106]S. F. Johnston, "The construction of colorimetry by committee", Science in Context (in press).

[107]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.

[108]For example, the opening pages of W. E. Barrows, Light, Photometry and Illuminating Engineering (New York, 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 light and colour by World War II.

[109]W. E. Forsythe (ed.), Measurement of Radiant Energy (New York, 1937), and P. Moon, The Scientific Basis of Illuminating Engineering (New York, 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, the product of a 'culture of unification' which had been nurtured at Nela Park since its foundation. Similarly Moon, an illuminating engineer and relative outsider to the scientific community, attempted to broach the separation by allying illuminating engineering with scientific principles.

[110]G. Lemaine, R. McLeod, M. Mulkay & P. Weingart (eds.), Perspectives on the Emergence of Scientific Disciplines (The Hague, 1976), p. 6.

[111]Ibid.

[112]J. Law, "The development of specialties in science: the case of *x*-ray protein crystallography", Science Studies 3 (1973), 275-303.

[113]Ibid., 303.

[114]Commercial products such as microdensitometers were eventually introduced in response to market demand.

[115]E.g. by John Walsh, who as a Section leader in the Electrotechnical Division of the NPL perhaps not surprisingly categorised photometry as an applied science and a branch of technical physics. Edward Hyde denoted it one of the "great middle fields of science" [E. P. Hyde, "The physical laboratory of the National Electric Lamp Association", The Illuminating Engineer **2** (1909), 758-61].

[116]D. S. L. Cardwell, The Organisation of Science in England (London, 1972), 229, 235.