

1995 DEXTER AWARD ADDRESS

THE CHEMICAL ORIGINS OF PRACTICAL PHYSICS

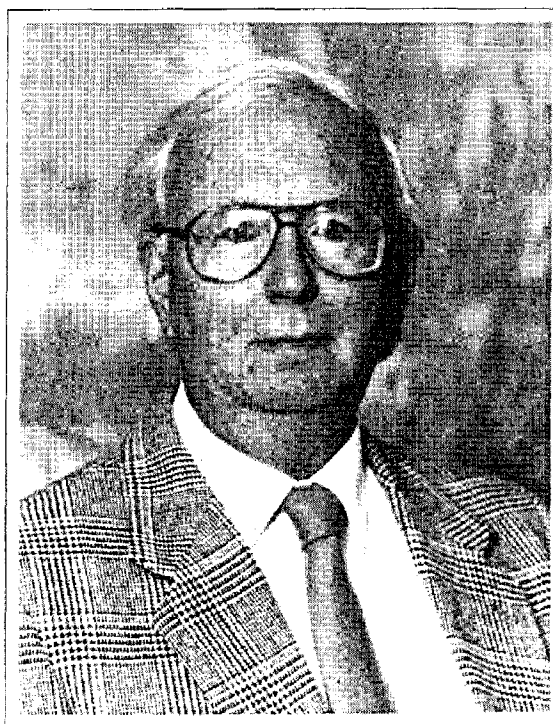
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I should like to thank the Dexter Corporation as well as the Chair and members of the Dexter Award Committee, both present and absent, for this honor. I feel proud to join the roster of a long line of distinguished historians starting with Ralph Oesper in 1956; and it is especially warming to join the list of many UK holders of this honor that began with John Read and has included such illustrious names as Douglas McKie, J. R. Partington, Joseph Needham, and more recently such friends as Trevor Williams, M. P. Crosland, Robert Anderson, and Colin Russell. This lecture is dedicated to the memory of the late Sidney Edelstein.

Apart from art and music, what distinguishes science, medicine, and engineering from all other forms of vocational training is the laboratory/workshop location in which it takes place. In this paper I look at the relation between nineteenth-century physics and chemistry and consider the development of practical physics teaching in the UK and USA.

I have taken as my motto a remark attributed to Bunsen by Sir Henry Roscoe: "Ein Chemiker der kein Physiker ist, ist gar nichts" – a chemist who isn't also a physicist is no chemist (1). Although a modern physicist might well construe this as confirmation that chemistry is merely a part of physics, chemists will accept it in the spirit that Bunsen intended, namely that chemists should be natural philosophers with a broader perspective and agenda than that of mere analysts; chemists explain physical as well as chemical properties, and to do that they must needs grasp and use the principles of mathematics and physics.

In fact, as many scholars have pointed out during the last decade or so, the discipline of physics as we know it today only emerged quite late in the nineteenth century, as reflected by the fact that both the British and



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French Physical Societies were founded in the 1870s (2). Before then, physics (or, strictly speaking, practical physics as opposed to mathematical physics which

did have its own autonomy) was very much part of chemistry, as early nineteenth-century textbooks confirm. Thus as late as 1867, the exciting contents of John Cargill Brough's short-lived *Laboratory* refer solely to chemical spaces, not physical ones.

Put another way, the imponderable bodies of heat, light and electricity remained part of chemistry until subsumed within the concepts of energy and electromagnetism in the 1850s and 1860s. It is not surprising, therefore, that many nineteenth-century chemists who implicitly followed Bunsen's later aphorism in their research activities, when seen from our later disciplinary perspective of physics, seem more like physicists than chemists. Faraday is the most obvious case, and others like André-Marie Ampère, Henri Regnault, Gustav Magnus, and Thomas Andrews easily spring to mind. Less well known are those cases of chemists who exploited their practical laboratory skills to create teaching programs in physics at the very time when the subject was emerging as an autonomous discipline in the 1870s. As George Carey Foster reminisced in 1914, "the transformation ..., from chemist into physicist was a fairly common phenomenon...(3)" This essay is principally about two of these chemists-turned physicists.

Like the 1960s and 1970s, the 1860s and 1870s were a golden age for new laboratories and academic buildings in Great Britain (4). In 1866 Carey Foster began to teach practical physics at University College – to be followed three years later by W. G. Adams at rival King's College. Between 1873 and 1874 the Cavendish physical laboratory was opened at the University of Cambridge, with fittings designed by James Clerk Maxwell based upon the experiences of the Clarendon laboratory at Oxford and of William Thomson's laboratory at Glasgow. In 1874 laboratories were opened at the new Royal Naval College at Greenwich, and science colleges were opened at Bristol and Leeds. In 1878 Alfred Waterhouse's gothic University College opened in Liverpool, with its extraordinary tiered chemical laboratory designed by James Campbell Brown; Sheffield responded with Firth College in 1879; and the decade ended in 1880 with the opening of Mason's College in Birmingham and the beginning of the new City & Guilds of London Institute's ambitious building program for technical education – completed in 1884 as Finsbury Technical College in the city of London and in 1885, at South Kensington, with Waterhouse's elegant Queen Anne-style Central Institution (5).

As implied, although the bulk of this building activity was devoted to opening larger and better facilitated chemistry laboratories, the decade also saw the

emergence of the physics laboratory – for *undergraduates and certificated students* as opposed to a laboratory space like Thomson's in Glasgow and Maxwell's at Cambridge in which advanced (postgraduate) students were encouraged to help a professor with a research problem (6). The pioneers here were undoubtedly two former chemists, George Carey Foster and Frederick Guthrie, the one at University College London, the other at the Royal School of Mines (or Normal School of Science as it became) in South Kensington. How and why did these two men turn aside from promising careers in organic chemistry for uncertain ones in physics teaching? Let's examine each man in turn and look for any common thread.

GEORGE CAREY FOSTER (1835-1919) (7)

A shy, nervous man and son of a Lancashire calico printer, Foster undoubtedly owed a debt for his career to the great theoretical chemist of the 1840s and 1850s, Alexander William Williamson, with whom Foster studied chemistry before briefly acting as his personal assistant from 1855 to 1858. In 1858 Williamson packed Foster off to the continent to study with Kekulé at Ghent, Jules Jamin in Paris (significantly a Professor of experimental physics at the Sorbonne who was much interested in electrical problems), and the young Privatdozent, Georg Quincke, at Heidelberg – a pupil of Bunsen's who was to spend a lifetime devoted to measuring and collecting data on the properties and constants of materials (8).

From these experiences Foster returned to Britain in 1860 not only *au fait* with Kekulé's structural theory, but with a deft hand in French and German experimental physics. Between 1857 and 1867 we find Foster addressing the British Association on organic nomenclature (e.g., he recommended the term isologous to indicate a difference of H_2 in a carbon series, on the analogy of Gerhardt's *homologous* for a difference of CH_2), and on "recent progress in organic chemistry." He also wrote up his Ghent work with Kekulé on hippuric and piperic acids. On his return Williamson had found a position for Foster in the private London laboratory of Augustus Matthiessen (another pupil of Bunsen's who emigrated to Britain in 1857) where Foster produced technically excellent work on the constitution of the alkaloid narcotine.

Meanwhile, in 1862, again due to Williamson and to his Scottish contacts, Foster was appointed to a chair at Anderson's College in Glasgow, not however in chemistry, but in natural philosophy. Perforce, therefore, Foster was obligated to lecture on these aspects of phys-

ics that he best knew from his training with Williamson as a chemist, and Jamin and Quincke as a physicist, namely heat and electricity. These were both subjects that he contributed articles on to Henry Watts's *Dictionary of Chemistry* in 1863. (Incidentally, how many of us have noted the significance of this publication which was hailed by William Crookes in the *Chemical News* on its completion in five volumes in 1868 as "the greatest work which England has ever produced on chemistry, [indeed] one of the greatest she has produced on any subject (9)?"")

While Foster was in Scotland, and building on the back of the introduction of the BSc degree within London University, Williamson and other senior professors at University College persuaded the decrepit Professor of Natural Philosophy, Benjamin Potter, to take early retirement. The Natural Philosophy chair was then divided into chairs of mathematical physics (awarded to the geometer, Thomas Archer Hirst) and experimental physics, which went to Foster in October 1865. As Keith Nier has noted in a Harvard thesis (10), at this stage, in 1863, Williamson's chemistry syllabus, which had hitherto contained a good deal of elementary heat, electricity, and optics, now became almost completely chemical because these subjects were now to be taught by Foster. The age of teaching physics separately from chemistry had begun in Britain as a by-product of London chemists' successful campaign to get science degrees awarded by the University of London. Coincidentally, of course, such a change also released valuable time for the rapidly increasing knowledge of organic chemistry that chemists like Williamson wanted to teach (11).

We need not follow Foster's spatial difficulties in teaching a physics of quantitative precision. Suffice to say that initially he had to make do with a room adjacent to the lecture theatre before gaining a couple of workshop/laboratory spaces in the basement of University College. Under these cramped conditions, and working for the British Association Committee on electrical standards, in 1872 he transformed the Wheatstone bridge into a precision instrument usually known in Britain as the Carey Foster Bridge. It is important to note that because apparatus was expensive, Foster and his mechanic (William Grant) often designed and made their own equipment.

In the 1870s Foster campaigned for physics teaching in schools, wrote and edited texts, and in the 1880s argued strongly for the importance of practical physics and the value of accurate measurement as a foundation for research (12). His reward came in 1893 when the

College erected the Carey Foster Physics Laboratory that was destroyed in the 1939-45 war, and knowledge that he had trained England's next generation of physicists such as William Ayrton, Oliver Lodge, and Ambrose Fleming. Foster retired in 1898, only to be made Principal (Provost) of the College, where he played a leading role in the negotiations that led in 1900 to the reconstitution of the University of London as both a teaching and examining body.

One pupil recalled (13):

His nervous manner prevented Carey Foster ever becoming a good lecturer, and his failure in this respect was due, in addition, to a conscientiousness that made it difficult for him to be content with a simple statement that he knew to be only an approximate expression of a truth, and at the same time made him reluctant to adopt the customary method of illustrating physical laws by the use of simple, although entirely imaginary, experimental data. In place of these, his illustrations would often consist of the actual results of laboratory measurements, and the younger students, unless they were of a rather exceptional type, were apt to lose both attention and interest in the details of laborious computation.

His patience in showing students how to conduct their experiments often involved him taking over completely. His character was not unkindly but shrewdly summed up by Oliver Lodge in the phrase: "He was far from fluent, and he was so conscientious about expressing himself correctly that sometimes he failed to express himself at all (14)."

FREDERICK GUTHRIE (1833-1886) (15)

If Guthrie is remembered at all by historians of science and education, it is the terrible portrait of him painted by H. G. Wells in his *Autobiography* (1933) that sticks in the mind. Wells trained to become a secondary school science teacher at the Normal School of Science at South Kensington in 1885. After praising Huxley's biology course for its abiding interest, Wells writes (16):

Now Professor Guthrie, the Professor of Physics, was a man of very different texture from the Dean. He appeared as a dull, slow, distraught, heavily-bearded man with a general effect of never having fully awakened to the universe about him.

Like Watson's unflattering portrait of Rosalind Franklin in *The Double Helix*, Wells was, I think, trying to give an honest impression of his feelings as a science student forty years earlier; he admits that he only learned later that Guthrie was suffering from a throat cancer at



Frederick Guthrie, courtesy Oesper Collection,
University of Cincinnati

the time of these impression in 1885; but unlike Watson, Wells, while admitting that he had been an unruly and unprincipled student, was unforgiving. Guthrie's cancer had only "greatly enhanced the leaden atmosphere of his teaching.....Quite apart from that, he was not an inspiring teacher... to put it plainly, [Guthrie] mandered amidst ill-marshalled facts. He never said anything that was not to be found in a textbook (17)."

Faced with such a brilliant demolition job (but note that Wells failed his Associateship), historians have been reluctant to accept that Guthrie, along with his colleagues at South Kensington T. H. Huxley and Edward Frankland, and later Henry Armstrong, William Ayrton, and John Perry, was one of the great innovators of Victorian science teaching. What are we to make of Guthrie's dedication, as recorded by Lodge (18):

There was a time when Guthrie lived a curious life; he would not leave his laboratory, even at night. He had a hammock rigged up, and used to live in the laboratory.

Guthrie, who was probably of Scottish ancestry, was the son of a London tailor. Two years older than Foster, like him he was educated at University College School and the College before studying chemistry with Graham and Williamson, as well as Henry Watts, who had been his private tutor until the age of twelve. Like Foster, Guthrie had gone to Germany in 1854 to work with

Bunsen at Heidelberg, and then under Kolbe at Marburg, which he described to his friend Henry Roscoe (whom he had met at University College London) as "this dreary valley of desolation (19)!" He seems, however, to have got on with Kolbe very well, the latter describing him as "a well-educated man ... very industrious .. and extremely nice (20)." What Guthrie made of Kolbe's unsuccessful use of him to try to refute Williamson's theory of etherification electrolytically would be interesting to know. The doctorate was earned successfully in 1856 from an experimental study of the salts and esters derived from amyl ether and led on to some eight papers on organic chemistry, including the first preparation of mustard gas in 1860. In view of Foster's work on narcotine, it is intriguing to note that Guthrie was the first chemist to point out the therapeutic action of amyl nitrite (the nitrous acid ester of isoamyl alcohol), though its use as a vaso-dilator in heart disease was not proven until the work of the pharmacologist, Thomas Lauder Brunton, in 1867. Brunton's studies were directly inspired by those of Alexander Crum Brown, the successor to Lyon Playfair at the University of Edinburgh. Guthrie had assisted Playfair in Edinburgh between 1859 and 1861, after serving in a similar capacity with Frankland at Owens College, Manchester from 1856 to 1859. Everything seemed to point Guthrie towards a successful career in chemistry.

However, in 1861 Guthrie made an extraordinary career move, inspired, perhaps, by his brother's growing success as a teacher in South Africa (21). Along with Walter Besant, the future novelist and literary critic, Guthrie became a Professor of Natural Philosophy at the Royal College in Mauritius. The former Ile de France, Mauritius had become an English colony after 1811 as a result of the Napoleonic Wars. When Darwin visited the island in May 1836 he found cultivated fields, sugar cane plantations, bookshops, opera houses, and tarred roads; this was confirmed by Besant who writes of its being "a gay and sociable place" where youth predominated (22). Besant writes of Guthrie as (23):

...a man of infinite good qualities. He was my most intimate friend from our first meeting in 1861 to his death in 1886. It is difficult to speak of him in terms adequate. He was a humorist in an odd, indescribable way; he did strange things gravely; he was a delightful donkey in money matters; when he drew his salary - £50 a month -- he prepaid his mess expenses, and then stuffed the rest in his pocket and gave it to whoever asked for it, or they took it. Hence he was popular with the broken down Englishmen of shady antecedents who hung about Port Louis. He never had any money; never saved any; always

muddled it away. Like many such men, he was not satisfied with his scientific reputation; he wanted to be a poet. He published two [pseudonymous] volumes of poetry, both with the same result. He was also clever as a modeller, but he neglected this gift. He did some good work in the colony in connection with the chemistry of sugar cane.

Guthrie's two poetic attempts are not without interest, for their subject matter on both occasions was the outsider: the Jew and the Gypsy. They were both published under the pseudonym of Frederick Cerny; whether the choice of name was significant, we cannot say. *The Jew* (1863), a Miltonesque and Dante-esque meditation on the problem of evil, seen through the eyes of a Jew who offered no solace to Christ on the march to Calvary, is not without fine moments, and may be interpreted as a defense of "seeking knowledge" in order to improve a sinful and intransigent world. A decade later, drawing upon one of the stories in George Borrow's *Gypsies of Spain*, Guthrie published an illustrated two-act metric drama, *Logroño* (1877). This passionate story of a scholar, a gypsy, and a lascivious count, surrounded by a chorus of courtiers, burghers, gypsies, peasants, and flower girls, reads like the libretto of a tragic opera. One cannot help regretting that Verdi or Puccini never came across the script.

Besant's reference to Guthrie's carelessness over money is interesting. Like the Anglo-German chemist, A. W. Hofmann, Guthrie married four times (three of his wives appear to have died in childbirth), and his widow and her three step-children were left in penury in 1886. Huxley launched an appeal in *Nature* and she evidently received a pension from the civil list (24).

It is Besant who also informs us that already in Mauritius, Guthrie was a confirmed agnostic, "who thought it his duty to learn such of the secrets of nature as he could, and not trouble himself about speculations as to the secrets of life, either before the cradle or after the grave (25)." This does much to explain how Guthrie got on so well later with Tyndall, Frankland, and Huxley at South Kensington. Guthrie was one of the new science professionals, convinced that science, not religion, was the key to human progress and happiness (26). Like Tyndall and Huxley, he lectured regularly to working-class men (27).

Examinations for The Royal College in Mauritius were administered by the University of London, but in the absence of a proper chemical laboratory there, Guthrie was thrown upon his own resources, investigating the physics of droplets and bubbles, analyzing local river water and commenting upon sugar cane. As Besant makes clear in his autobiography, the professoriate was

unhappy with the Principal, an ex-Austrian army officer who continually upset the local French population. Eventually Besant complained to the island's Governor, who carried out a Commission of Inquiry. Although the Principal was eventually removed, his reinstatement in 1867 brought about Besant's and Guthrie's resignation in 1867 and their return to England.

Back in England, Guthrie landed on his feet teaching science at Clifton College, Bristol, the proprietary school which was also later to have John Perry, Arthur Worthington, and William Shenstone on its staff, and Eric Holmyard in the twentieth century. Here he polished off a paper on heat which he sent to John Tyndall, who arranged for publication, and who saw to it that Guthrie succeeded him at the Royal School of Mines in Piccadilly, London a year later. In 1872 the School was to move to South Kensington, where Huxley, Frankland, and Guthrie had improved laboratory facilities for teaching practical biology, chemistry, and physics. At this Normal School of Science, Guthrie and his colleagues not only trained would-be science teachers like H. G. Wells, but under the sponsorship of the Department of Science and Art they were able to set up annual summer schools to improve the practical teaching skills of existing teachers.

As Jensen noted some years ago in *Chemistry in Britain*, Guthrie joined the Chemical Society in April, 1868, and promptly described a voltastat to deliver a constant voltage from a battery, and offered an intriguing paper "On graphic formulae." The latter suggested the replacement of Crum Brown's recently introduced graphic formulae by pictorial geometrical symbols which indicated combining power. At the meeting Guthrie's suggestion was treated with derision by William Odling and it led to some correspondence in *Chemical News* and, amusingly, to some buffoonry at the B-Club to which both Foster and Odling belonged (28).

In reply, Guthrie showed his sense of humor in retorting that Odling's own dash valency notation was in reality a system of graphic formulae (29):

Dr. Odling appeared shocked at the idea of an atom of nitrogen supporting three "sticks" one in each hand, and one on its head. Strange objection from one who years ago trained his atom of nitrogen the much more difficult acrobatic feat of balancing simultaneously three sticks on the tip of its nose, - N"

While on the subject of Guthrie's sense of humor and geniality even when under attack, let me mention two other examples that seem to confirm that Wells unfortunately completely misinterpreted his teacher's personality.

First, in the Christmas issue of *Nature* in 1879, writing under the pseudonym A. von Nudeln (i.e., Mr Macaroni), Guthrie humorously ridicules a recent spate of German writings on geometry and mathematical physics with a letter entitled "On the Potential Dimensions of Differentiated Energy"(30):

In his great work, which appears to be but little known in England, *Ueber die stille Bewegung hypotetischer Körper*, Professor Hans points out that the dimensions of 'ideal' matter may not only differ in degree, but also in kind. He deduces by means of implicit reasoning from his three primitive 'stations,' that not only must there be space of 4, 5, 6, etc. dimensions, but also that there must be space of -1, -3, -5, etc. and that there may be space of -2, -4, -6 &c dimensions. Pursuing Hans's train of thought further, Lobwirmiski has quite recently interpreted space of 1.1, 1.2, 1.3 &c dimensions...the same philosopher has also conclusively shown that space of $n \rightarrow -1$ exists [with] all the properties of angular magnitude; like all partly bounded infinities (*theilweise begränzte Unendlichkeiten*), it is unmagnifiable.

This piece of drollery ends with an obscure proof that the moon is, indeed, made of cheese. Guthrie's mixture of simplicity and wisdom, kindness dashed with a pungent, but never caustic, humor, led one anonymous friend (perhaps Besant) to compare him with the Uncle Toby immortalised by Laurence Sterne in *Tristram Shandy* (31).

This spoof probably supports Foster's contention in an obituary that Guthrie, though trained by Augustus De Morgan in mathematics, "was somewhat apt to underrate the scientific importance of the work of mathematical physicists in comparison with that of pure experimentalists (32)." His concentration on the physics of real things like drops and bubbles; thermal conductivity of liquids; salt solutions; the discovery of "cryohydrates;" and the melting points of eutectic mixtures, and his use of a very informal, homespun language to describe nature – all of this seems to have been anathema to James Clerk Maxwell (33). Although Guthrie was elected to the Royal Society in 1873, as a referee Maxwell continually found fault with papers that Guthrie submitted to the Royal Society; and this was undoubtedly the principal reason why Guthrie founded the Physical Society at the end of 1873 (34).

It is again a remarkable example of Guthrie's ability to deflect criticism that in 1878 he was able to reply jokingly to Maxwell's pretty intemperate review of his textbook, *Practical Physics, Molecular Physics and Sound* (35). Maxwell's particular gripe seems to have been Guthrie's language of exposition. For example, he

picked upon the way Guthrie formulated a variation of Hooke's law concerning the elongation of a wire, so that if a length m is extended to become n , the original diameter becomes $d^\circ m/n$. The formula is correct, so presumably Maxwell thought it odd for Guthrie to say it is true if one assumes "the volume of the metal remains approximately unchanged." Guthrie's revenge was a splendid verse *a la Maxwell* and in Scots dialect (35).

"Remonstrance to a Respected Daddie anent his loss of temper"

WORRY, through duties Academic,
It might ha'e been
That made ye write your last polemic
Sae unco keen:
Or intellectual indigestion
O' mental meat,
Striving to solve some question
Fro' "Maxwell's Heat".
Mayhap that mighty brain, in gliding
Fro' space tae space,
Met wi' anither, an' collidin',
Not face tae face.
But rather crookedly, in fallin'
Wi' gentle list,
Gat what there is nae help fo' callin'
An ugly twist.
It 'twas your "demon" led ye blindly,
Ye should na thank him,
But gripe him by the lug and kindly
But soundly spank him.
Sae, stern but patronising daddie!
Don't ta'e't amiss,
If a puir castigated laddie
Observes just this: —
Ye've gat a braw new Lab'ratory
Wi' a' the gears,
Fro' which, the warld is unco sorry,
'Maist naught appears.
A weel-bred dog, yoursel' must feel,
Should seldom bark.
Just put your fore paws tae the wheel,
An' do some Wark. $d^\circ m/n$

Gooday has argued that following the 1867 Paris Exhibition and the success of the electric telegraph, the scientific community was able to promote the teaching of precision measurement in physics laboratories on the assumption that "hands-on" experience was better than teacher demonstration if precision were to be achieved.

In the first place, this would be good for encouraging rational and accurate reasoning within liberal education; and in the second, it would be a scientific alternative to "rule of thumb" methods of industrial apprenticeship, the need for which the electric telegraph had exposed (36). The problem was how to put this into effect. There were three common solutions put into practice in the 1870s (37).

In the first, chemistry model: every student would have had a similar collection of apparatus. While this worked cheaply and well in chemistry, where practical work depended on little more than a set of test tubes, some filter and litmus paper, and a bench stock of standard chemicals, it would have been expensive to achieve the same goal in elementary physics teaching, where relatively expensive optical and electrical apparatus were necessary. Two alternative solutions to the problem of expense were therefore tried during the 1870s: one emanated from the Massachusetts Institute of Technology and spread to Europe; the other was developed by Guthrie at South Kensington.

One of the more remarkable graduates of MIT in 1867 was Edward Charles Pickering (1846-1919), a graduate from the Lawrence Science School at Harvard. William Barton Rogers, MIT's Principal, who thought that the Lawrence School was taking the wrong approach to science teaching, and believing that America desperately needed practical astronomers and physicists rather than engineers, appointed Pickering to MIT with the specific intention of introducing practical physics teaching into the curriculum. Encouraged by Rogers, in the fall of 1868 Pickering fitted up a student laboratory at Boston. With no European model to draw upon, and ignoring any chemical precedent, Pickering devised his own set of physics experiments, apparatus, and instructions for students to follow.

In Pickering's system of instruction, which was ultimately cheap to operate and destined to become universally adopted in schools and universities, students worked singly or in pairs at different experiments, and proceeded in rotation from one experimental table to the next. Only one set of experimental apparatus was therefore needed per student pair. At each bench point students received written instructions on what to do, record, and interpret. These experiments on techniques of measurement, the properties of gases, sound, the mechanics of solids, and the nature of light (including photography), having been tested out at MIT for some three or four years, were published by Pickering in 1873 as *Elements of Physical Manipulation* (38). By then he was able to draw upon the influential German text on university laboratory physics by Friedrich Kohlrausch

(39). A second volume, largely devoted to electricity – "a subject better adapted than any other to the laboratory system" – appeared in 1876 and included an appendix which offered advice on the planning of physical laboratories.

Not surprisingly in view of the fact that Pickering's text was reviewed in Norman Lockyer's *Nature*(40), Lockyer gave publicity to the MIT program in the Sixth Report of the Devonshire Commission on Scientific Instruction, of which he was Secretary (41). Knowledge of Pickering's method of multiple experiments was picked up quite quickly in Britain, probably from both the *Nature* review and from the Devonshire Commission. For example, in an essay on the teaching of physics published by Foster in the *Educational Times*, he referred approvingly to the "American" method of multiple classroom experiments (42).

It seems clear, then, that for anyone planning to develop a new physics teaching laboratory in the 1870s, the proven experience of the MIT laboratory would have been a good model to copy. The fact that William Ayrton, the electrical engineer, left London to teach at the Royal Engineering College in Tokyo in 1873, only a few months after the appearance in Boston of the first volume of Pickering's treatise, is suggestive. For it was in Japan that Ayrton and his mechanical engineering and mathematical colleague, John Perry, put the multiple experiment model of teaching into great effect. On their return to London, they made this method of practical instruction famous at the Finsbury Technical College, from where it was adopted by the Cavendish Laboratory and other physics teaching institutions (43).

Although this method of instruction was destined to become universal and is to this day the preferred method of teaching practical physics, there would have been initially high start-up costs. Indeed, until such times as instrument makers were geared up to making sturdy, cheap but reliable Wheatstone bridges, galvanometers, lens systems, etc., Guthrie's alternative approach must have seemed ingenious.

In Guthrie's system, detested by H. G. Wells, but much admired by writers in *Nature*, students were required to make their own apparatus, before manipulating it experimentally (44). Guthrie gave a long account of the method and the educational philosophy behind it in his Cantor Lectures to the Society of Arts in 1885 (45). A decade earlier, in 1875, either he or William Barrett informed *Nature*'s readers of the method's educational advantages (46).

Students unaccustomed to manipulation find to their astonishment, when they begin, that all their fingers have

turned into thumbs, and they are amazed at their clumsiness and stupidity. Very soon, however, fingers begin to reappear, and the very first successful piece of apparatus that is made gives them a confidence in themselves which they had thought impossible to attain. The pleasure of having made an instrument is increased a hundredfold when it is found that by their own handiwork they may verify some of the more important laws of physics.

Since the final examination depended entirely upon the accuracy and reliability of the apparatus constructed by the student, there was additional incentive to manipulate with care and exactitude (47).

It must not be thought that students were literally expected to make apparatus from scratch. Guthrie's purpose was certainly not to train and produce instrument makers. Apart from needing their own set of tools – a hammer, nails, and other basic tools – in practice they received a kit which Guthrie's workman had already prepared and which they individually assembled by following printed instructions (48):

[The student] receives the wood and metal ... cut in pieces of the right size. He must have to acquire a little skill in bending and blowing glass, and in the use of the soldering iron. But what human being should be without this?

The cost of materials for making the apparatus was some £2, compared with the cost of purchasing a set from a supplier for about £15 – a saving to the Department of Science and Art of £13. Moreover, the student (49): finds himself at the end of the course with a set of apparatus made by himself, and fully tested by himself; and he finds himself in possession of verifications of many of the great generalisations of physics, which generalisations, having been thus acquired by the simultaneous working of brain and hand, he is slow to forget.

Although Guthrie did not mention it, the method also had an advantage over Pickering's system insofar as a newly-certificated science teacher from South Kensington could bring his own set of apparatus with him to his new school teaching post. This would have been important where finances were tight and a new teacher had first to consolidate his position in a school before he could argue for the purchase of apparatus from instrument suppliers.

Finally, we should note the wider influence of Guthrie on physics teaching in his capacity as examiner for Department of Science and Arts examinations in heat, light, sound, electricity, and magnetism. Just as Edward Frankland exploited his examination position to lay down a chemistry syllabus and to demand that all stu-

dents either witnessed or conducted a definite number of experiments (50), so did Guthrie. In 1881 Guthrie's *Outline of experiments and description of apparatus and material suitable for illustrating elementary instruction in sound, light, heat, magnetism, and electricity* was published by the Department of Science and Art for science teachers. These recommendations not only influenced physics teaching in Britain but also in Japan and America. Kannosuke Yoshioka, the Japanese translator of Guthrie's *Practical Physics* (1877), incorporated Guthrie's recommendations and also arranged for a set of apparatus to be displayed at the Tokyo Education Museum from 1895 (51). It appears, then, that Guthrie played a significant posthumous role in rendering Japanese science teaching less didactic and more practical.

In America, there was little "hands-on" experimental work by high school students until the 1890s. Dr Alfred Gage, who opened an English (*sic*) High School in Boston in 1880 and who published a practical text, *Elements of Physics*, in 1882, significantly abandoned teaching in order to make and supply scientific instruments for school use. In the same decade, Frank Wigglesworth Clarke's report on the state of physics and chemistry teaching in American city schools showed that less than ten percent possessed laboratories (52). This situation began to change during the 1880s when Charles William Eliot, President of Harvard University, and himself a trained chemist, deliberately placed physics on the list of matriculation requirements. This led Edwin H. Hall, Professor of Physics at Harvard, to draw up the influential *Harvard Descriptive List of Elementary Physical Experiments* in 1886. By 1902, Hall was able to claim that practical physics teaching in American high schools was in advance of anything to be found in Europe (53).

Initially, in 1886, Harvard allowed two alternatives: either a written examination based upon designated textbooks of astronomy and physics; or a practical demonstration based upon the matriculant's school experience of Hall's "course of experiments in the subject of mechanics, sound, light, heat, and electricity, not less than 40 in number (54)." Although these 40 experiments were chosen from American texts like Pickering's *Physical Manipulation*, they were also considerably influenced by British sources such as Guthrie's *Practical Physics* and A. M. Worthington's *Physical Laboratory Practice* (1886). By the 1890s, Harvard insisted upon practical experience of physics for its entrants to science courses. We may, therefore, conclude that, directly or indirectly, Guthrie also influenced the rise of the elementary physics laboratory in America.

By way of conclusion, I draw attention to the organic chemist Henry Edward Armstrong who, writing in 1933, a year before Wells's cruel portrait of Guthrie appeared in his autobiography, gave a Huxley Memorial Lecture in South Kensington. In this Armstrong suddenly makes an aside (55):

Good as was the top floor [Huxley], it was being beaten, down below in the basement, by the chemist-turned-physicist, Guthrie, who developed a logical, practical course, on self-help lines, of extraordinary value—long since on the scrapheap, I fear, given its final quietus by the all-pervasive electron. It is little short of shameful that South Kensington has let this go by the board – unrecorded. Real earthly physics is a fast-disappearing art. Cannot someone be found to recover the course, if only to put it away in a case in the British Museum, as a monument of a former greatness.

Perhaps this essay goes some way towards satisfying Armstrong's hope. By recalling Bunsen's aphorism and by resurrecting Foster and Guthrie from the scrapheap of history it has been possible to reveal something of their and other chemists' roles in the establishment of practical physics teaching.

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5. Besides my article cited in Ref. 4, see Sophie Forgan and Graeme Gooday, "A fungoid assemblage of buildings. Diversity and Adversity in the development of college architecture and scientific education in 19th-century South Kensington," *History of Universities*, **1994**, 13, 153-92.
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15. Obituaries include: C. Foster, *Nature*, **1886-1887**, 35, 8-10, and *Proc. Phys. Soc.*, **1887**, 8, 9-13; *Proc. Geol. Soc.*, **1887**, 43, 48. Intriguingly, unlike Foster, Guthrie has an entry in *Dictionary of National Biography*, but he was ignored by the Chemical Society despite having been a fellow since 1868. For Guthrie's papers, see *Roy. Soc. Catalogue of Scientific Papers*, Ref. 7, seriatim.
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