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The postwar American scientific instrument industry

Sean F. Johnston
University of Glasgow[1]

1. Introduction

The production of scientific instruments in America was neither a postwar phenomenon nor dramatically different from that of several other developed countries. It did, however, undergo a step-change in direction, size and style during and after the war.

The American scientific instrument industry after 1945 was intimately dependent on, and shaped by, prior American and European experience. This was true of the specific genres of instrument produced commercially; to links between industry and science; and, just as importantly, to manufacturing practices and cultures. I will argue that, despite the new types of instrument commercialized after the war, this historical

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[1] University of Glasgow Crichton Campus, Dumfries DG1 4ZL, UK; s.johnston@crichton.gla.ac.uk

continuity of links with science and scientists guided and constrained the design and manufacture of these products. Nevertheless, new designers, manufacturers and customers gradually transformed the culture of scientific instruments in the second half of the century.

2. Scope

This chapter deals with a subset of the American instrument industry, namely the measuring and monitoring instruments manufactured for scientific use. Even with the specification of ‘scientific’ instruments, however, these borders are rather artificial and unclear: instrument making from the seventeenth through the twentieth century has generally involved the fabrication of both standard products and custom-made devices for scientific use.[2] In this context of sales quantities, ‘scientific’ instruments have often been defined as low-volume, special-order or custom devices. In a similar vein, ‘scientific’ instruments were commonly distinguished from ‘production’ instruments by context of usage, namely their very absence from – and indeed irrelevance to – production environments. This demarcation according to customer and environment was mirrored in at least one further respect: the training of their users. The classification into ‘scientific’ and ‘engineering’ applications was as fluid as the relationship between American universities and technical industries themselves. Despite these complementary definitions, the notion of the ‘scientific instrument’ was beginning to prove inadequate even at the turn of the twentieth century, and dramatically so when discussing the post-Second World War period.

Definitions altered qualitatively after the Second World War in at least three further ways: (a) new genres of device altered the scope of the scientific instrument; (b) the contribution of State and military sponsorship of new forms of instrument became significant; and, (c) the postwar demand for specialist instruments increased rapidly, owing to wartime innovation, new applications and new customers. I will explore the evolution of instrument manufacturing in this changing context of new technology, funding, development and markets.

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[2] Williams, Mari, *The Precision Makers: A History of the Instruments Industry in Britain and France, 1870-1939* (London: Routledge, 1994).

3. Scene-setting: the precursors to postwar industry

The manufacturing industry relating to instrumentation in its widest sense extends back easily through the nineteenth century, and much further if the definition of ‘instrumentation’ is broadened to include metrological devices such as navigating, surveying and examining instruments. This traditional instrument-making activity, well-established as a crafts-based industry by the seventeenth century, produced products such as astrolabes, transits, telescopes and microscopes, which combined skills in optics and metal working to yield fine lenses, scales and mounting systems. Such products were manufactured for recognizably similar purposes, using similar methods, through the 1950s and into the 1960s.

From the 1850s, newly invented electrical technologies were creating new industries and, with them, new forms of scientific instrument. The introduction of the electric light bulb in the late 1870s, for example, led to scientific and industrial research into photometry for the dual purposes of elucidating characteristics to improve design, on the one hand, and providing data – via measurements of intensity, stability and power consumption – for commercial competition with gas lighting, on the other.[3] Optical instruments such as commercial photometers were consequently added to the repertoire of opto-mechanical instrument makers.

From the second half of the 19th century, electrical instruments such as galvanometers, ammeters, voltmeters and ohmmeters were designed and constructed initially by scientists themselves, and soon marketed by the instrument makers who made more advanced prototypes for them.[4] More than was the case for optical shop-work, which demanded highly skilled manual labor for polishing, these new electrical devices eventually could be made in part, at least, by specialized piece-work and assembly-line methods.

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[3] Johnston, Sean F., 'Making light work: practices and practitioners of light measurement', *History of Science* 34 (1996): 273-302.

[4] Gooday, Graeme J. N., 'Teaching telegraphy and electrotechnics in the physics laboratory: William Ayrton and the creation of an academic space for electrical engineering in Britain 1873-1884', *History of Technology* 13 (1991): 73-111.

This close connection between natural philosopher-inventors and instrument manufacture, a cultural outcome of the Scientific Revolution, had developed further during the nineteenth century. The collaboration between chemist Joseph Black and artisanal instrument-maker James Watt in the late 18th century, for example, led not only to practical steam engines, but also later to measuring instruments important for the industry. The British natural philosopher David Brewster early in the following century invented the kaleidoscope and stereoscope, both of which were popularized with commercial versions as ‘philosophical instruments’. William Thomson (later Lord Kelvin) was simultaneously involved through his career in high science, the practical engineering arts, and commercial instruments. During the construction of the transatlantic telegraph cable in the late 1850s, Thomson was scientific advisor and a cable company director. Researching the electrical principles of bandwidth in cables, Thomson invented the mirror galvanometer, a particularly sensitive instrument for the measurement of electrical current that benefited telegraphic communication. He also invented, patented, and commercialized designs for a marine compass and instruments for the measurement of tides and the gauging of sea depth. When he retired from his university post in 1899, Thomson joined with James White, a ‘philosophical instrument maker’ who had built electrical balances, electrometers, compasses and sounding apparatus to his designs, to form a scientific instrument company. The company, Kelvin and White, survived a century by merging with smaller firms. By the end of the nineteenth century, other large companies such as Siemens in Germany and Barr and Stroud in Britain were supplying standardized instruments to their respective military and to a growing assortment of commercial customers.[5]

These examples illustrate the Victorian integration of science and industry and, along with them, the closer alliances, and even merging, of the identities of scientist and artisan. Such cases became a stream by the turn of the twentieth century, and led to a growing number of firms reliant on scientific design expertise and catering to

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[5] Cahan, David, *An Institute for an Empire: The Physikalisch-Technische Reichsanstalt, 1871-1918* (Cambridge: Cambridge University Press, 1989); Johnston, Sean F., 'The Physical Tourist -- Glasgow: a heritage tour', *Physics in Perspective* 8 (2006): 451-65.

scientific markets.[6] Indeed, after the First World War, Imperial College London recognized this trend by appointing a Professor of Instrument Design.[7] By 1923, the raised profile of scientific instruments and their designers led to a dedicated British periodical, the *Journal of Scientific Instruments*.[8] A similar American periodical, the *Review of Scientific Instruments*, joined it in 1930.[9]

4. Domestic roots

Like Britain and continental Europe, the American instrument industry had traditional roots in opto-mechanical and magnetic navigation instruments. Its scientific connections were considerably weaker, however, because of its relatively few universities during the nineteenth century and lack of an established research tradition, especially after the 1862 Land Grant Act, which instead encouraged academic activities relevant to agriculture and industry. American instrument manufacture was also small in scale and not linked strongly to industries such as glass production, which did expand significantly during the century.[10]

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[6] Cattermole, M. J. G., A. F. Wolfe and Thomas B. Greenslade, *Horace Darwin's Shop, A History of the Cambridge Instrument Company 1878 to 1968* (London: Adam Hilger, 1987).

[7] Pollard, A. F. C., 'Notes upon the mechanical design of some instruments shown at the exhibition of the physical and optical societies', *Review of Scientific Instruments* 5 (1928): 184-90.

[8] Only in 1990 was the journal renamed *Measurement Science and Technology* to reflect the decline in instrument design and fabrication by scientists. By this time, most instrument design had been appropriated by companies employing industrial scientists, a change of culture that had begun a half-century earlier.

[9] The *Review of Scientific Instruments* was an outgrowth of the *Journal of the Optical Society of America*, because most publications on scientifically generated instruments of the period concerned optical devices. Nevertheless, according to Shinn (op.cit.), after the formation of the journal, articles on chemistry and the burgeoning domain of electronics soon represented half of the total.

[10] Dyer, Davis and Daniel Gross, *The Generations of Corning: The Life and Times of a Global Corporation* (Oxford: Oxford University Press, 2001).

By the beginning of the twentieth century, however, a dozen American engineering schools were teaching over 8000 students per year, and the National Bureau of Standards was formed to research evaluation methods, standardize tests and ensure collaboration between State and industry. And closer links between universities and large companies led to the formation of research laboratories within major firms to focus on industrially relevant problems, in some cases by paying close attention to fundamental science.[11] Early examples included the General Electric and Bell companies.[12] As those two corporate examples suggest, the center of mass of apparatus towards electrical devices.

One marker of the rapidly evolving instrument industry was the birth of new organizations. In 1902 the first organization grouping manufacturers, the Scientific Apparatus Makers of America, was founded in Pittsburgh, Philadelphia. As the first such organization in the country, it sought to represent the broadening group of instrument designers and artisans. While membership was a mere 200 at its inception, it had risen by tenfold eighteen years later. Most members nevertheless worked in a company environment much like their nineteenth century analogs: few instrument manufacturing firms had more than 30 employees, and many had much fewer. The distribution of instrument companies also conformed to established manufacturing centers along the east coast and Midwest, particularly in Pittsburgh itself, Philadelphia, Boston, Chicago and Detroit.[13]

The turn-of-the-century organization and growth in instrument manufacture was bolstered by an interwar equivalent. In 1937, a national congress devoted to

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[11] Noble, David, *America by Design: Science, Technology and the Rise of Corporate Capitalism* (New York: A. Knopf, 1977).

[12] Wise, George, 'A new role for professional scientists in industry: industrial research at General Electric, 1900-1916', *Technology and Culture* 21 (1980): 408-29; Reich, Leonard, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876-1926* (Cambridge: Cambridge University Press, 1985).

[13] Shinn, Terry, 'Strange cooperations: the U.S. Research-Technology perspective, 1900-1955', in: B. Joerges and T. Shinn (ed.), *Instrumentation: Between Science, State and Industry* (Dordrecht, 2001), pp 69-96.

instrument manufacture was held in Pittsburgh, sponsored by the Honeywell Company and its Brown division. Like its sponsor, the congress focused on instrumentation and control engineering. A strong attendance led to a second congress in 1939 and a new organization, the American Society for Measurement and Control, in 1941. In combination with America's subsequent entry into the war and the consequently accentuated need for instrument production, the instrument industry was revitalized.

5. Wartime demands and postwar redefinitions of the scientific instrument

The Second World War promoted new instrument technologies and new principles of instrumental design and operation. It accelerated an ongoing transition of laboratory culture by making scientific instruments more ubiquitous and by extending the laboratory from a research environment to a production environment. And the war also permanently altered the scale and organization of the American instrument industry.

Following Pearl Harbor, America's production of explosives, fuels, armaments, ships, aircraft and motor vehicles escalated dramatically. This production increasingly was monitored and quantified by instruments at the point of manufacture. The wartime chemical industry, in particular, demanded spectroscopic analyses to control the production of products such as petroleum derivatives and synthetic rubber.

Spectrometers, as a general class of instrument, had the most profound effect in creating new wartime and postwar instrument markets. Spectrum analysis, a growing scientific study from the late nineteenth century, had been crucial to the development of the twentieth century science of quantum mechanics, but was simultaneously developed by physical chemists to identify and, in some cases, quantify, unknown materials. *Atomic emission* spectrometers, for example, allowed industrial researchers to identify the composition of steels; *atomic absorption* spectrometers could quantify chemical components in solutions. During the 1930s, applications of spectrochemical analysis were extended to biochemistry, mineralogy and agricultural chemistry. Such instruments became the center of spectrochemical laboratories situated within a growing number of manufacturing businesses between the wars.

The first of these emission and absorption spectrometers measured visible light by employing the eye for observations. Recording of spectra by photographic film dramatically extended their capabilities, however. A photographic record could be better calibrated, monitored and verified, allowing improved accuracy. This indirect form of analysis also allowed for operators having less training, and for higher speed of determinations. And photographic recording opened the analysis to the ultraviolet portion of the spectrum. When the war began, such spectrometers were increasingly designed to obviate human analysis of the direct spectrum at all: it became progressively more common to incorporate a photoelectric sensor and optics to scan the film record to yield an electrical readout of a spectral line's density or, with electromechanical linkages, a tracing of its variation across the spectrum.

Such ultraviolet/visible (UV/VIS) spectrometers, initially based on the recording of spectra on photographic film and followed by analysis of the spectral lines using a microdensitometer, were powerful but still relatively slow. Wartime demand for rapid production measurements led to the merging of photoelectric sensors and increasing use of electronics to calibrate the measurements and provide direct read-outs of quantity.[14]

One of the most important early examples was the Beckman DU ultraviolet spectrometer introduced by National Technical Laboratories (NTL) in 1942.[15] Although not the first such instrument, it found a large market because of its integrated packaging – which demanded little operator setup – and its recognition by the National Bureau of Standards as a key device for standard tests of vitamin A in foods. It proved equally valuable in other biochemical monitoring, such as for penicillin production later in the war.

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[14] Hentschel, Klaus, 'Visible and ultraviolet spectroscopy and spectrochemistry', in: R. Bud and D. A. Warner (ed.), *Instruments of Science: A Historical Encyclopedia* (New York, 1998), pp 752-4; Jarnutowski, Robert, John R. Ferraro and David C. Lankin, 'Fifty Years of Commercial Instrumentation in Spectroscopy, Part II: Landmark Instruments in UV/Vis', *Spectroscopy* 7 (1992).

[15] Beckman, A. O., W. S. Gallaway, W. Kaye and W. F. Ulrich, ' History of spectrophotometry at Beckman Instruments, Inc.' *Analytical Chemistry* 49 (1977): 280A-300A

Undoubtedly the most important example of the new instrument industry, however, was the infrared spectrometer.[16] More specifically than do visible and ultraviolet spectra, the infrared portion of the spectrum reveals the molecular composition of solids, liquids and gases. Understandings of the correlation between functional groups of molecular species and the infrared spectrum had been extended from the early twentieth century. By 1940 this provided reliable identifications for a growing range of chemical species – particularly organic compounds – and was increasingly coupled to theoretical understandings.[17] Quantitative analyses were also becoming possible, although instrument instabilities limited this application until improved and increasingly automated and compensating instruments were developed during the war.

Despite its utility for war work, the infrared spectrometer nevertheless had characteristics that demanded new user practices. As it did not employ photographic film, the laboratory darkroom and its associated skills were irrelevant for infrared studies. Instead, the instrument was reliant on infrared sensors that converted infrared energy to an electric signal. Such sensor and amplifier systems had been developed from the 1920s and by the beginning of the war provided reliable results for users expert in electronics and infrared optics.

Probably the most important wartime application for infrared spectrometers was the measurement of butadiene concentration, which was the essential component of synthetic rubber production; indeed, this single application was responsible for the sponsored development of the instrument. In 1942, the newly founded Office for Rubber Reserve consulted National Technical Laboratories, Perkin-Elmer and Shell development about a suitable instrument, and selected the Shell design, by Robert Brattain, to be fabricated by Arnold Beckman’s NTL company as the Beckman IR-1. While one hundred were ordered for use during the war, the company was restricted by contractual obligations from promoting its instrument, and commercial sales were low. Alternate and improved designs were devised by other manufacturers, the most important of which was the Perkin-Elmer Model 12, introduced in 1944. The Perkin-

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[16] Johnston, Sean F., *Fourier Transform Infrared: A Constantly Evolving Technology* (Chichester: Ellis Horwood, 1991).

[17] Stoicheff, Boris, *Gerhard Herzberg: An Illustrious Life in Science* (Ottawa: National Research Council of Canada, 2002)

Elmer Company, founded in Boston in 1937 to manufacture optics for astronomical applications, had diversified at the onset of the war to produce optics for mass-production items such as cameras and periscopes. Its infrared spectrometer design proved encouragingly successful, and a second version, the Model 21 introduced in 1950, captured a rapidly growing market and allowed a significant expansion of the company.[18]

The high wartime production rate and increased demands for efficiency encouraged the development of automated instruments; the formation of the American Society for Measurement and Control is an indication of this new engineering orientation.**[19]** The wartime evolution of automatic recording instruments altered manufacturers' expertise and users' perceptions of their own role. By obviating point-by-point measurement, automation could allow greater precision. Without human intervention between the sensor and the recording pen, more rapid and, at times, more accurate results could be achieved. And, for busy industrial and governmental laboratories, automatic instruments could dramatically improve throughput, require less qualified labor, and yield cost savings by operating beyond work shifts.

Simple recording instruments had been common in physiological research since the turn of the century but, with the increasing sophistication of electronics and integrated optical and mechanical design, became more widespread in physics and engineering just before the Second World War.[20] Cybernetics – initially conceived as a science of control processes, and later oriented toward the goal of embedding intelligence or

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[18] McDonnell Jr, H. G., 'The evolution of analytical instrumentation at Perkin-Elmer', *American Laboratory* 21 (1980): 95-101

[19] Noble, David, *Forces of Production: A Social History of Industrial Automation* (Cleveland: Press of Case Western Reserve University, 1984).

[20] Bennett, Stuart, 'The development of process control instruments: the early years', *Transactions of the Newcomen Society* 63 (1992): 133-64. For one of the earliest examples, see Randall, H. M. and John Strong, 'A self-recording spectrometer', *Review of Scientific Instruments* 2 (1931): 585-99. The paradigm of such automatic instruments was the recording spectrophotometer designed by Arthur Hardy in 1928, and marketed by General Electric in 1935.

human attributes into machines – was an outgrowth of wartime research into the principle of feedback. For a time, this new scientific field and design theme motivated postwar scientific instruments manufacturers. The theory of servomechanisms was increasingly identified as important to the design of electronic amplifiers, automatic pen recorders and energy-compensating spectrometer slit-width adjustments – indeed, precisely the novel components of postwar scientific instruments. Coined by MIT mathematician Norbert Wiener in 1948, the ‘cybernetic’ principles behind such ‘teleological mechanisms’, or goal-directed machines, which first had been envisaged for automatic anti-aircraft gunnery, soon were applied to the more mundane scientific application of automatic recording instruments.[21] Thereafter, in combination with the nascent field of cybernetics itself, automatic instruments flourished. The diverse examples include the Coulter counter, an electronic instrument for the counting of small particles such as granules and biological cells[22] and the dilatometer, a specialized device to measure changes in mechanical specimens with temperature.[23] As mentioned in the context of Beckman and Perkin-Elmer, the automation of spectroscopic instrumentation became a particular focus of American instrument companies.

Typical of this evolution was the postwar ‘Quantometer’, a specialized direct-reading spectrometer designed to monitor five, and later more, spectral emissions. Often finding employment for the measurement of metallurgical composition, it was designed to display elemental compositions on dials, and provided rapid throughput of samples specifically in production laboratories. It was emblematic in redefining the categorization of scientific instruments. Reliant on the same principles as a laboratory spectrometer, it was nevertheless designed to require minimal expertise from their

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[21] Bennett, Stuart, *A History of Control Engineering, 1930-1955* (Stevenage: Peter Peregrinus, 1994).

[22] Coulter, Wallace H., 'The Coulter counter', in: (ed.), *Instruments of Science* (London, 1998), pp 153-4.

[23] Redfern, John, 'The Dilatometer', in: (ed.), *Instruments of Science* (London, 1998), pp 173-5.

(non-scientist) operators and usually monitored a production, rather than an experimental, context.[24]

The Quantometer's more complex cousins, the infrared spectrometers, remained embedded in a laboratory context; indeed, their reliance on hygroscopic optical components, careful optical alignment and mechanically-sensitive infrared detectors sometimes relegated them to specially outfitted room+s. Nevertheless, the increasingly reliance of industrial, academic and governmental laboratory staff on spectrometers altered the very nature of a chemical laboratory from one based on the traditional chemical manipulations of so-called wet chemistry to high-throughput analysis and record-keeping. Further commercial instruments soon joined them, based on techniques developed in the decade before or after the war: mass spectrometry,[25] gas chromatography, and nuclear magnetic resonance (NMR)[26]. For biologists and physicists, x-ray crystallography[27] and the electron microscope[28] provided dramatically extended vision. Collectively, these instruments gave new

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[24] Hasler, M. F., R. W. Lindhurst and J. W. Kemp, 'Quantometer, a direct reading instrument for spectrochemical analysis', *Journal of the Optical Society of America* 38 (1948): 789-93.

[25] Reinhardt, Carsten, *Shifting and Rearranging: Physical Methods and the Transformation of Modern Chemistry* Science History Publications, 2006).

[26] Lenoir, Timothy and Christophe Lécuyer, 'Instrument Makers and Discipline Builders: The Case of Nuclear Magnetic Resonance', *Perspectives on Science* 3 (1995): 276-345. The technology was later adapted to create Magnetic Resonance Imaging (MRI) for the new market of medical instrumentation. See, for example, Wehrli, Felix W., 'The origins and future of nuclear magnetic resonance imaging', *Physics Today* 45 (1992): 34-42.

[27] Hunter, Graeme K., *Light is a Messenger: The Life and Science of William Lawrence Bragg* (Oxford: Oxford University Press, 2004).

[28] Rasmussen, Nicolas, *Picture Control: The Electron Microscope and the Transformation of Biology in America, 1940-1960* (Stanford, CA: Stanford University Press, 1997).

powers of identification, quantification and structural determination.[29]

6. Instrument manufacturers

Just as the war redefined laboratory practice via instruments, it also refocused and integrated the American instrument industry. It had suddenly increased the demand for novel instruments, and encouraged manufacturers to envisage automated devices. More subtly, government contracts had impelled firms to collaborate and develop new business networks. Thus the traditional optical manufacturing company Bausch and Lomb was encouraged to establish (but ultimately rejected) a business arrangement to provide components for the NTL Beckman IR-1 spectrometer; by contrast, Perkin-Elmer provided optics for an American Cyanamid spectrometer, and used this newfound expertise to enter the instrument industry with its own products. Even more subtly, the wartime supply contracts made all American instrument manufacturers increasingly reliant on government development projects as the most regular route to financing new commercial products.[30]

Illustrating this new growth for the instrumentation industry on its established foundations, the Instrument Society of America was founded in 1948, again in Pittsburgh.[31] And two local organizations, the Society for Analytical Chemistry of Pittsburgh and the Spectroscopy Society of Pittsburgh held a joint conference from 1950, which became the annual focus for the American instrument industry thereafter.

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[29] On this transition in chemical practice, see, for example, Bud, Robert and Susan E. Cozzens (ed.), *Invisible Connections: Instruments, Institutions and Science* (Bellingham, 1992); Baird, Davis, 'Analytical Chemistry and the ‘Big’ Scientific Instrumentation Revolution', *Annals of Science* 50 (1993): 267-90; and, Morris, Peter J. T. (ed.), *From Classical to Modern Chemistry: The Instrumental Revolution* (Cambridge, 2002).

[30] To give one pertinent example, Perkin-Elmer became a major contractor for a series of NASA and Defense Department projects for satellite optical systems during the 1970s and 80s, and by so doing extended its capabilities in high precision optical fabrication.

[31] Shinn, op. cit.

The commercialization of NMR instruments by Varian Associates illustrates features of instrument manufacturing shared by a number of other postwar companies. The war had expanded American engineering expertise in two regions, linked closely to universities that had engaged in substantial wartime research: the Boston/Cambridge area (owing to the research and development work at MIT, Harvard and pre-existing companies such as Perkin-Elmer), and central and southern California, owing to activities at Stanford University – later to be the nucleus of Silicon Valley – and Caltech, in Pasadena. Varian, for example, was founded in 1948 in Palo Alto, California, where it enjoyed strong staff links with physics and electronic engineering at Stanford University. Income for its first two decades was largely based on military contracts for research and development of instruments. The company broadened its activities, though, by conceiving a commercial NMR spectrometer for chemical applications, selling during the 1950s to petroleum and other chemical companies.[32] As suggested by their company names, similarly dual-income strategies were pursued by firms such as Baird Associates in Cambridge, Massachusetts; National Technical Laboratories (renamed Beckman Instruments in 1950) in Pasadena, California and Applied Research Laboratories (ARL) in Glendale, California.

7. Designers and customers

The origin and extension of instrument companies often relied on a network of expert engineers or industrial scientists seeding new firms and bringing with them established design philosophies and manufacturing styles.

A typical example is the Fourier-transform spectrometer. First conceived by physicists and astronomers in America, Britain and France immediately after the Second World War, this radical form of spectrometer was manufactured in the early 1960s for two distinct applications: for laboratory physicists exploring the far-infrared portion of the spectrum, and for airborne or satellite-borne military reconnaissance. The first commercial manufacturers (the British firms Grubb-Parsons and the Research and Industrial Instrument Company (RIIC), later purchased by Beckman)

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[32] Reinhardt, Carsten, 'A lead user of instruments in science: John D. Roberts and the adaptation of nuclear magnetic resonance to organic chemistry, 1955–1975', *Isis* 97 (2006): 205-36.

were based on designs developed by physicist Alistair Gebbie at the National Physical Laboratory. Gebbie, some twenty years later, also collaborated with Lloyd Instruments to introduce a third design.[33] An RIIC engineer, Ray Milward, later seeded a French instrument company (CODERG).

If the British version of the Fourier transform spectrometer can be traced to one seminal design, the same is true for the original American variant. During the late 1950s, physicist Lawrence Mertz at Baird Associates conceived new design principles for the Fourier spectrometer. When he and two associates left to form Block Associates (later Block Engineering) in 1960, they focused on military contract work.[34] Mertz proposed his innovative design for use in environments where rapid measurement of faint spectroscopic information was essential. Between 1966 and 1968, three companies (Block Engineering, Fabri-Tek (later Nicolet) and Dunn Associates) combined to sell commercial versions of his instrument. Quantities remained limited, however: some thirty units were sold, mainly to industrial research laboratories.[35] From 1968, Digilab, a subsidiary of Block Engineering manufactured what were by then known as Fourier Transform Infrared (FTIR) spectrometers to a new market: analytical chemists.[36] Their instruments were sufficiently ‘black boxed’ to restrict the number of interventions required by their users to keep them optically aligned and functional. A number of other North American companies (including Idealab, General Dynamics, Analect, Bomem and Perkin-Elmer) manufactured such instruments from the 1970s, usually as a combination of custom-made designs for

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[33] Johnston, Sean F., *Fourier Transform Infrared: A Constantly Evolving Technology* (Chichester: Ellis Horwood, 1991).

[34] Johnston, Sean F., 'In search of space: Fourier spectroscopy 1950-1970', in: B. Joerges and T. Shinn (ed.), *Instrumentation: Between Science, State and Industry* (Dordrecht, 2001), pp 121-41.

[35] Dunn, S. T., 'Fourier transform infrared spectrometers: their recent history, current status and commercial future', *Applied Optics* 17 (1978): 1367-73.

[36] Hirschfeld, Tomas, 'New trends in the application of Fourier transform infrared spectroscopy to analytical chemistry', *Applied Optics* 17 (1978): 1400-12.

military, space, meteorological or other government activities and volume-produced devices for commercial use by analytical chemists.

This transition required a cultural revolution for both the manufacturers and their customers. The instrument manufacturers were required to adapt to higher expectations of reliability and performance from their chemist customers and, in particular, to make their equipment behave more like the now traditional dispersive (prism- and grating-based) infrared spectrometers. Those chemists who were brave 'early adopters', in their turn, found their instrumentation skills expanded by these new and demanding instruments. This alteration carried with it commercial advantages: manufacturers found themselves supplying a growing range of standard 'sampling accessories' for chemists who were emboldened by the extended instrumental capabilities. The result was an increasingly standardized form for the commercial FTIR spectrometer and its optical accessories, along with a new orthodoxies in sampling methodologies for analytical chemistry.[37]

By the mid 1980s, FTIR spectrometers had almost completely replaced dispersive infrared instruments in the chemistry market, and had become one of the more ubiquitous components of a typical chemistry laboratory. FTIR instruments also led a trend towards computer analysis and, later, computer control of instruments.[38] FTIR spectrometers were reliant upon a computer to transform their encoded data into a spectrum. During the early 1960s, they depended on the off-line analysis of the measured data by a mainframe computer. By the end of the decade, though, it became practicable to employ a minicomputer to do the number crunching immediately after the measurement sequence and eventually to set up, run and analyze an experiment. This delayed analysis – initially seen by customers as a serious disadvantage – was recast by manufacturers as being an advantage: computer analysis of digital data

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[37] These new sampling methodologies included attenuated total reflectance (ATR) sampling of liquids, diffuse reflectance infrared Fourier transform (DRIFT) and Kubelka-Munk analysis of powders, and photo-acoustic spectroscopy (PAS).

[38] During the early 1950s, there was limited commercial application of punched card databases for infrared spectrometers. However, the relatively slow, labor-intensive and expensive data processing equipment, combined with poor wavelength accuracy of the spectrometers, precluded extensive data analysis, and had poor market uptake.

could extract considerably more information from measurements for these very precise instruments. Thus vector arithmetic (the additional, subtraction and division of entire spectra) came to be a desirable side effect that allowed FTIR instruments to compete even more successfully with their postwar dispersive counterparts. With the rising ubiquity of FTIR instruments in chemistry laboratories and the simultaneous rise of inexpensive personal computers, laboratories were even further computerized from the 1980s. Continuing this trend, Laboratory Information Management Systems (LIMS) were developed to store, display and further manipulate digitally acquired data, and later to integrate laboratory instruments.

8. Manufacturing processes

Until the 1980s, the annual production of instruments such as NMR and FTIR spectrometers was typically less than a few hundred per company, with total sales of the order of 1000 internationally. Such numbers corresponded to those of traditionally defined scientific instruments, and there was considerable continuity with pre-war processes, even though the instruments themselves were of novel varieties. Relatively low-volume research instruments continued to employ the established pre-war style of manufactured elements such as simple metal castings, manually constructed cable harnesses and hand assembly. Optical components, particularly awkward materials such as the hygroscopic prisms, lenses and beamsplitters used on infrared instruments, were frequently shaped and polished by hand. By the 1980s, on the other hand, the design process for mechanical and electronic subassemblies was increasingly performed with the assistance of computer-aided design (CAD). Outsourced printed circuit boards replaced in-house production, and optical components were increasingly machine-produced by subcontractors in moderate batches. This became a significant factor in optical design, because aspherical machined mirrors improved performance and simplified design without raising cost.

Even for such low-volume products, however, design and manufacture were streamlined to ease assembly and adjustments in the field. So-called kinematic mounts – first introduced by the Cambridge Instrument Company in the 1920s – were employed with increasing frequency in automated instruments by the 1970s to assure enduringly aligned and stress-free fixations for optical components and electromagnetic subassemblies. Such design engineering had the dual advantage of lowering production costs and reducing the need for traveling service engineers, which seriously constrained international sales.

9. Sales, support and development

Concerns for convenient maintenance were motivated by the increasingly complexity of scientific instruments, which now commonly incorporated sophisticated electronic, mechanical, optical and electromagnetic elements. The strong reliance on the traveling engineer, however, was a key characteristic of postwar scientific instruments.

A culture concerning the sale, installation and commissioning of stock scientific instruments grew from the practices familiar for custom-designed instruments. Purpose-built instruments traditionally required discussions between the customer and designer at the time of order; delivery of the instrument to the customer's site, often accompanied or followed by an installation engineer; and, a negotiated series of performance tests to validate the suitable functioning of the device. These procedures became a commonplace for the postwar instrument manufacturers working under government or military contracts, with contract payments frequently tied to the achievement of design, delivery and specification targets. When these companies introduced standardized products for commercial customers, this close liaison continued; as companies grew, their specialized labor also expanded. Deciding on the appropriate location of this expert labor, though, was contentious.

This division of labour and understanding of customer support relied on transferring a culture of scientific and engineering laboratories to the customer's workplace. This culture involved a close identification between designer and user. Both were assumed to be interested in modifying and improving their apparatus; this, in turn, demanded a particular theme of instrument design, incorporating adaptability and accessibility. It required trained users rather than inexpert customers. The relationship was sometimes fraught between physicist/engineer designers and users from other disciplines. The case of Fourier spectrometers, for example, illustrates diffidence among the creators of such instruments and new types of user. One key innovator, a physicist, observed:

> A major novelty is the mass intrusion of chemists upon the scene, and there is no doubt this is mainly due to the availability of commercial

> instruments. On the whole this is a healthy development we must applaud, a mark of maturity for the Fourier technique. It means the benefits will be made available to many groups where instrumental development cannot be achieved, and it should greatly increase the over-all scientific output.... There is little doubt that if you are an instrument builder, your viewpoint differs greatly from that of the person who buys a ready-made interferometer; the words Fourier spectroscopy are apt to mean entirely different things in both cases. I personally have some doubts about Fourier spectrometers being used properly even when producing indisputably fine results.[39]

Instrument customers, he argued, could never be as competent in the use of their purchases as could the designers. Indeed, some manufacturers counseled their customers to appoint specialist instrument tenders:

> The author feels quite strongly that the ideal operation of an FT-IR system should be a closed shop with one key operator. Furthermore, the key operator should be electronically oriented with a background in both machine language and high order programming. This type of key operator can easily be trained in infrared sample handling and would provide an ideal interface between the analytical chemist and the system, leaving the analytical chemist free to devise challenging experiments for FT-IR and the operator to implement these experiments through full utilization of software and hardware capabilities.[40]

As the market expanded beyond physicists comfortable with this culture to chemists requiring workhorse instruments for busy laboratories, however, manufacturers increased their markets by expanding their support network of installation and maintenance engineers. Such support networks carried a high price for both

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[39] Connes, Pierre, 'Of Fourier, Pasteur, and sundry others.' *Applied Optics* 17 (1978): 1318-21; quotation p. 1321.

[40] Dunn, S. T., 'Fourier transform infrared spectrometers: their recent history, current status and commercial future', *Applied Optics* 17 (1978): 1367-73, quotation p.1372.

manufacturers and customers. Instrument companies found their opportunities for international expansion constrained by the need for local, or quickly transported, service engineers. The solution typically was to engage in agreements with national or regional companies as sales agents, with their engineers trained at or by the instrument company. Customers absorbed this cost in the price of the instrument and often in subsequent service contracts.

A further distribution of expertise was the adoption of ‘application engineers’. Often employed directly by instrument manufacturers, these engineers, generally trained as scientists to postgraduate level, would develop measurement techniques and recommend instrument adaptations to suit particular customers’ problems or develop new markets. Applications engineers also played a role in educating their customers in new techniques, and, in effect, adapting them to the machines. They thus extended and institutionalized the informal model of postwar manufacturers to liaise with customers and to modify their equipment to suit new niches. The Perkin-Elmer Corporation built a market for their Model 21 infrared spectrometer in 1950 by conducting short courses and meetings to educate chemists.

While this division of labor became the norm for postwar instrument manufacturers, it restricted the proliferation of instruments that were seen increasingly as routine and necessary. The expansion of production opened a gulf between the originally small instrument companies and their customers. Instrument manufacturers sometimes established poor relationships with international customers reliant on the communications and business relationships mediated by their agents, and uncompetitive with new firms established in the customer’s territory. Consequently manufacturers, at least for some lines of instruments, sought to engineer them for ease of use and reliability by non-expert users. Automated instruments, employing a combination of simplified and rationalized design alongside self-monitoring operations aided by microprocessors, reduced the need for delicate installation at the time of delivery, and subsequent expensive maintenance visits.

The postwar instrument industry thus relied upon a labor infrastructure and cultural practices that restricted its market penetration. Installation, maintenance and applications engineers provided by the manufacturers interfaced with on-site technicians to disseminate the expertise of the instrument more widely than in pre-war usage. Despite trends towards efficiently engineered and automated instruments, however, by the end of the century this redistribution of expertise was still not complete.

10. Conclusions

The late twentieth century American instrument industry has strong roots in older European and indigenous practice. The scientific instrument industry changed direction and expanded after the Second World War under the dual influences of military support for research and development and the widespread adoption by industrial and university scientists – particularly chemists – of new instrumental techniques. The market grew over several decades, however, and manufacturing methods and designs evolved slowly from traditional fabrication techniques that required considerable user adjustment, towards mass-produced and increasingly black-boxed and automated products. The opening of new markets for instruments – moving from fundamental researchers habituated to building their own equipment to those requiring higher-throughput, standardized measurements – constrained this growth, however. The increasingly sophisticated postwar instruments required a support network of installation engineers, applications scientists and maintenance contracts. This infrastructure showed signs of being subsumed within increasingly autonomous and reliably engineered instruments by the end of the century, but the industry continued a transition to a new culture of instrument designers, manufacturers and users.

11. References

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