Historic England

Science Laboratories to 1900

Introduction to Heritage Assets

Summary

Historic England's Introductions to Heritage Assets (IHAs) are accessible, authoritative, illustrated summaries of what we know about specific types of archaeological site, building, landscape or marine asset. Typically they deal with subjects which lack such a summary. This can either be where the literature is dauntingly voluminous, or alternatively where little has been written. Most often it is the latter, and many IHAs bring understanding of site or building types which are neglected or little understood.

This IHA is intended to provide an overview of the history of laboratory buildings, in order that important surviving buildings can be identified and understood in their proper context. The cut-off date of 1900 has been chosen a number of reasons. First, owing to the long pre-history of the laboratory, the centrality of the Victorian era, and the massive growth of science in the twentieth century, finishing at 1900 offers a means of establishing the history of the laboratory in a limited space. Second, it was around the turn of the twentieth century that standards were established for institutional (school and university) teaching and research laboratories, so at least in this area a degree of stability took over from continual change. Third, the challenges of describing twentieth-century laboratories are different in kind from those relating to laboratories up to 1900, owing in large part to the massive growth in specialized research laboratories in government, industry and academia.

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Front cover: The laboratory of the Royal Institution, c.1819.

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Introduction

The laboratory is the pre-eminent space of scientific work: an area in which elements of nature can be isolated from disturbance and precisely manipulated for productive or experimental purposes. It is hard to conceive of science without laboratories, and yet their ubiquitous presence is a relatively recent phenomenon.

The development of combined teaching and research laboratories in universities dates from the second half of the 19th century. Many specific disciplines – including physics, physiology, botany and mineralogy – only became 'laboratory sciences' around the same time. Widespread provision of school laboratories and separate technical schools emerged after the Great Exhibition of 1851, with the establishment of the Government's Science and Art Department and subsequent passing of the 1889 Technical Instruction Act. Industrial research laboratories, likewise, are products of the Victorian era. Further information on the relationship between architecture and public support for the sciences can be found in the Historic England IHA entitled Mechanics' Institutes (see also section 1.4 below).

Yet the story of the laboratory stretches back much further than this. As a space for manipulating nature, the laboratory has a history rooted in alchemy, metallurgy and pharmacy. We should think of these early laboratories as specialized workshops, closer to forges, foundries and kitchens than our own pristine scientific establishments. It was discipline of chemistry that was first gradually consolidated, in the 18th century, into a modern laboratory science. The 'laboratory revolution' of the 1860s–1880s – which followed earlier developments on the Continent – led to the design of the modern teaching and research laboratory, and the extension of practical instruction to the life sciences, physics, geology, psychology and other sub-disciplines.

The central idea of the laboratory is that the building should be designed and fitted out in such a way as to minimize interference with whatever procedures are to be conducted. James Clerk Maxwell gave the definitive statement of this in an 1876 essay:

> *In designing an Experiment* the agents and phenomena to be studied are marked off from all others and regarded as the Field of Investigation. All agents and phenomena not included within this field are called Disturbing Agents, and their effects Disturbances; and the experiment must be so arranged that the effects of these disturbing agents on the phenomena to be investigated shall be as small as possible.

This functionalist ideal has triumphed in the 20th century, especially at large experimental facilities, and most dramatically at particle accelerators, where entire buildings and even sites are essentially parts of the experimental apparatus. The history of the laboratory to 1900 is the story of how we reached this point: on the one hand it is about the development and specialization of the sciences themselves; on the other it is about the invention of a particular kind of space, which has deep historical roots but which could only take on its modern form once the first transformation had taken place.

1 Historical Background

1.1 The earliest laboratories

The early history of the laboratory is inextricably linked to the history of chemistry, though we must revise our modern understanding of that term by including alchemy, and by thinking of chemical procedures as specialized workshop activities, rather than purely experimental researches. Since antiquity there have been spaces set aside for certain activities involving the heating, treating and separating of substances. With only a few exceptions these were focused on practical ends: the preparation of dyes, the mixing of medicines, the manipulation of metals and the creation of alloys, and so on. In the late sixteenth-century the older term 'laboratory' began to be associated with sites of alchemical investigation. By extension the term could then be applied to the preparatory rooms in apothecary's shops, places in which assaying was done, and then any site in which natural substances were altered or produced by instrumental means.

An early insight into the the wide range of places in which such investigations could occur is provided by the episode of Martin Frobisher and the fool's gold he brought back from Newfoundland in 1577 and 1578. On the return of Frobisher's first voyage, a small amount of black ore was sent by his collaborator Michael Lok for analysis by William Williams at the Mint and George Needham at the Mines Royal. In spite of their assurances that the ore was worthless, an Italian assayer resident in London, Jean Baptista Agnello, declared that the sample contained both gold and silver. Further trials were made in private residences in Lambeth, High Holborn and near the Tower of London. Eventually a furnace was set up at Dartford by Jonas Schutz; this appears to have been located at the site of the present Hawley Mill, Sutton-at-Hone. The absolute failure of the Frobisher group to extract gold or silver from their ore is less important than what the events reveal about metallurgy in this period. Owing to the scale of investment in Frobisher's second and third voyages to retrieve ore, the question was of national importance, and the sheer number of locations in which precise (if erroneous) assays could be carried out is impressive. Notable also is that John Dee took an interest in the Frobisher ore, using his own private alchemical laboratory at Mortlake to conduct assays.

By the mid-seventeenth century laboratory spaces could be found in apothecaries' premises, instrument-makers' workshops, metallurgical facilities and anatomical theatres. The most substantial of these laboratories was constructed in London, at the Society of Apothecaries (1672). Like almost all early laboratories, this facility was moved and altered many times over the years, and the original rooms are no longer extant. ‘Laboratories’ for the production of gunpowder were set up first at Greenwich and then in the 1690s at Woolwich Arsenal: two parts of the latter are extant and are Grade II listed.

1.2 ‘Houses of experiment’

Another important strand in the history of the laboratory is the history of experiment. This concept acquired something like its modern meaning in the seventeenth century, with the arrival of newly invented optical and ‘philosophical’ instruments like the microscope and air-pump, and the idealized locale of ‘Solomon’s House’. The latter was a place of practical learning, popularized by Francis Bacon in his 1627 *New Atlantis*. It was not typically understood as an actual building or institution, at least until the 1680s, when the University of Oxford built the first Ashmolean Museum. This incorporated the collection of rarities and curiosities amassed by Elias Ashmole, as well as a lecture theatre and, in the basement, a chemical laboratory. The building was finished in 1683, at which point the naturalist Robert Plot was appointed keeper of the museum and ‘Director of Experiments’. Plot taught three times a week until his resignation in 1689, and had an assistant, Christopher White, who had trained with Robert Boyle and Peter Stahl. The Old Ashmolean building survives, as the

Figure 1: The Old Ashmolean building, Oxford; completed 1683. The laboratory occupied the basement.

History of Science Museum; archaeological excavations in 1999 revealed many of the original pieces of laboratory equipment, and have allowed something of the working life of the building to be reconstructed (Fig 1).

Until the construction of the Ashmolean Museum, the kind of inquiry described in New Atlantis took place in private residences or the practical spaces described above. Seventeenth century locations include Ragley House in Warwickshire, Towneley House in Lancashire, Samuel Hartlib's house in Charing Cross, Kenelm Digby's house in Covent Garden, William Petty's lodgings at 'Buckley Hall' in Oxford, Thomas Willis' house Beam Hall, Robert Boyle's three residences at Stalbridge in Dorset, Oxford (High Street), and London (Pall Mall). King Charles II even had a laboratory built at Whitehall, for the use of the physician and alchemist Edmund Dickinson.

Aside from the manor houses, in which rooms were given over to experiments, the only surviving building from this list is perhaps the most important: Buckley (or 'Bulkeley') Hall (now 107 High Street) was where the 'Experimental Philosophy Club' met between 1649 and 1651, and it was this group that went on to found the Royal Society in 1660 (Fig. 2; listed Grade II*). The building has a long and complex history before and after the mid-seventeenth century, when it was occupied by Petty and, below him, an apothecary's shop.

This pattern – chemical laboratories as practically-focused workshops, and domestic spaces adapted for experiment – carried on throughout the eighteenth century. The decline of alchemy and the rise of the idea of 'useful knowledge' consolidated the role of chemistry, which became a fashionable activity, and was promoted through new textbooks and lecture courses. Meanwhile the associations with alchemy and metallurgy were gradually cast off, though we should still think of chemistry in this period as fundamentally a science of separating and recombining compound substances: it was a science of production, and its products were inevitably destined for commerce. Nevertheless, chemistry was beginning to be seen as a 'science' rather than an 'art', and was gaining in status owing to this change.

Figure 2: 107 High Street, Oxford, formerly known as Buckley Hall; home of William Petty in the 1640s and meeting place of part of the group that went on to found the Royal Society.

Institutional laboratories were few and far between, but private laboratories proliferated. William Lewis' laboratory at Kingston is perhaps the best-known of these (see below). Notable examples were also built in the grounds of Christ Church (listed Grade II), and at William Brownrigg's estate in Northumberland, Ormathwaite Hall; these are both rare survivals from this crucial phase in the growth of chemistry. The Ormathwaite laboratory in particular was the site of important researches (listed Grade II). Brownrigg was a physician, trained at Leiden in the 1730s. Like Lewis, he also had interests in metallurgy, and conducted the first experiments on platinum, described in a 1749 paper presented to the Royal Society. At Ormathwaite Brownrigg also conducted the first systematic research into the nature of the dangerous 'damps' (gases) encountered in mining.

Yet Brownrigg's and Lewis' specialized laboratories were the exception, and a 'laboratory' in the eighteenth century most likely referred a domestic room given over to experiment. Many of the most important discoveries and researches in the period were made in rooms like this, in particular those of Joseph Priestley at his various residences in Nantwich, Warrington, Leeds, Calne (Bowood House), and Birmingham. Of these the house in Nantwich survives, as does the house at Bowood (listed Grade I), in which the original laboratory space is preserved. In addition to these domestic experiments, many were carried out in settings that could hardly be called laboratories at all – for example, some of Priestley's researches in Leeds were carried out in a neighbouring brewery. At the Royal Laboratory, Woolwich Arsenal, meanwhile, William Congreve transformed the production of gunpowder into something approaching an experimental science, including systematic testing and even theoretical explanation.

Congreve's case illustrates that around 1800, in the context of the Industrial Revolution, there was broad change in the fortunes of the sciences. A wide range of problems and areas of inquiry were considered nationally and internationally important. Systematic analysis and formal explanation were increasingly favoured over traditional know-how. Old spaces like the Royal Laboratory now became sites of experimental production, and new buildings were set up for the investigation of nature.

1.3 The 'chemical revolution' and the 'laboratory revolution'

By the end of the eighteenth century the sciences – especially chemistry – were undergoing a rapid transformation. In France a new kind of laboratory had been set up, at enormous expense, by Antoine Lavoisier. It was Lavoisier, too, who pioneered a standard vocabulary for chemistry, providing the prototype of chemical formulae. This was integral in the shift in emphasis in chemistry from the production of substances to their analysis. In his researches, too, Lavoisier was a pioneer, in particular in his experiments on combustion and the nature of gases, which crucially involved the precision measurement of the products of chemical reactions.

Concurrent (and seemingly at odds) with Lavoisier's new general programme of research was an increased specialization, both within chemistry and across the sciences, which began to take their modern disciplinary shape. Owing to this, and to the emphasis on precision measurement, spaces for science now needed to be more appropriately fitted to the experimental apparatus they contained. Lavoisier himself took an earlier invention – the jar inverted over water to collect gases – and made it the centrepiece of his experimental programme.

In England the new confidence in chemistry, and the Lavoisier-style analysis of gases, led to the opening of laboratories such as Thomas Beddoes' Pneumatic Institution, at his residences in Bristol (listed Grade II*). Far grander and more ambitious in its public and disciplinary scope, however, was the Royal Institution, founded in 1799 (listed Grade I). The RI was primarily intended as a place of public education, but it has also contained various research laboratories over the years, and is famous as the site of researches by Humphry Davy, Michael Faraday and many others (Fig 3). This public-minded sense of a new place for science and technical education lies behind two trends that had important architectural ramifications: the Mechanics' Institute movement and the rise of the 'Literary and Philosophical' societies. The fortunes of the

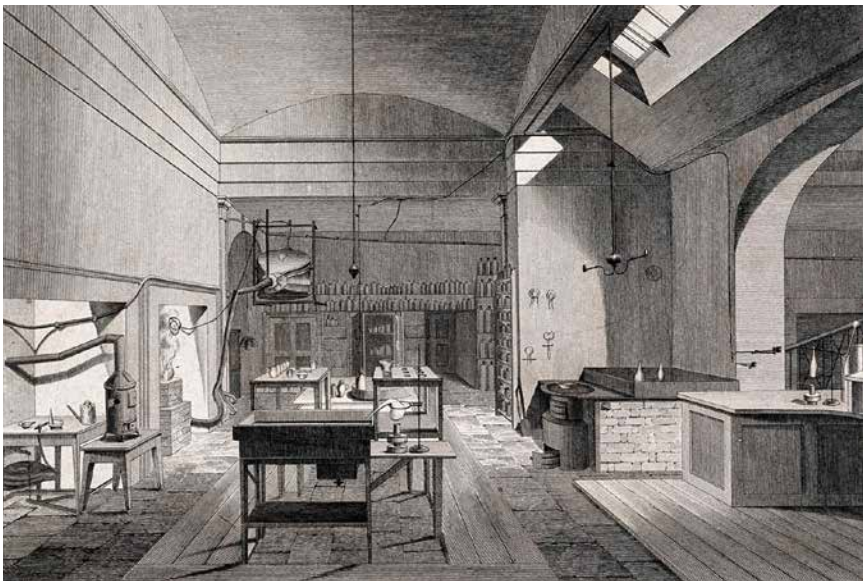

Figure 3: The laboratory of the Royal Institution. Note that this laboratory – famous for the research conducted there – was in fact not solely dedicated to that function: on the right can be seen the podium-end of one of the Institution's lecture rooms, for which the laboratory served as a preparatory space.

laboratory can also be traced in these buildings, which at first offered mainly theoretical and lecture-based instruction in the sciences, but which often incorporated practical and laboratory techniques through the nineteenth century.

Soon after Lavoisier's work and its reception in England, another kind of revolution was to take place, this time having to do with the training of research scientists. The broad contours of this change have to do with the growing status of science in society, manifest in new career opportunities for scientists, new associations and clubs, increased government funding, new university and school courses, and a sense of professional identity forged by all these factors and more. Although laboratories had, as we have seen, existed in one form or another for many centuries, the phenomenon commonly known as the 'laboratory revolution' in the sciences has its origins in the 1820s – specifically in the laboratory set up and run by Justus von Liebig at Giessen, from 1824. The design of the laboratory itself was not particularly radical – in fact it was a repurposed barracks. Yet in its purpose it was new: Liebig's was the first laboratory in which large numbers of students were trained specifically for a research career in chemistry. The only comparable institution in Britain was Thomas Thomson's Glasgow laboratory, which was influential in its own right – though, like Liebig's laboratory, it was more notable for its function as a teaching laboratory than its form, which is merely recorded as being 'a damp ground-floor room'. It was to Liebig's Giessen laboratory that a generation of scientists would travel, bringing back with them a vision of research schools based on laboratory training.

This should make clear that even by the 1840s the dominant laboratory science was chemistry. In fact, with the consolidation of chemistry as a research activity, its hold on the idea of practical research and instruction in the sciences had strengthened. What we would think of as the physical sciences of heat, electricity and light were considered part of chemistry until the middle of the nineteenth century. Around this time social, institutional and intellectual changes led to the development of the modern scientific disciplines as research and teaching activities. At a societal level, science was growing in importance and was increasingly a matter of state concern; new institutions were being formed, in particular government laboratories, and old institutions (especially the Universities of Oxford and Cambridge) were undergoing dramatic reform; within the sciences disciplinary divides were developing, most importantly between chemistry and physics, with the concepts of energy and electromagnetism serving as a unifying framework for the latter. Science was increasingly taught in schools, and this in turn led to the demand for qualified teachers. The professional activities that a working scientist could pursue were multiplying, and again this put pressure on the higher education system to respond with new courses and exams.

Practical classes were added to courses in medicine, botany, physiology, mineralogy and zoology. All of these demanded new spaces; at first these were to be museums, but quickly the desire for laboratories took over, and new buildings were commissioned. To the older universities were added new university colleges at Manchester, Bristol, Newcastle, Liverpool, Birmingham and London. All of these were the sites of important laboratories set up in the late-nineteenth century. Technical colleges were the next development that led to a boom in laboratory building.

1.4 Support for science in the Victorian era

Alongside laboratories for teaching and research, by the middle of nineteenth century a number of Government laboratories had been established. In 1842 the Customs Laboratory was opened in Gresham House, London, subsequently moving and changing its name several times. As ‘The Government Laboratory’ it received its first substantial accommodation under the direction of Thomas Thorpe in 1897 (in buildings in Clement’s Inn Passage, London, since demolished).

As seen above, Woolwich had long been the site of important research into explosives, and it was there in 1864 that a chemical laboratory was built for Frederick Abel, who had been Ordnance Chemist for a decade by that point (listed Grade II). Abel was involved in the layout and design of the laboratory, which featured innovations such as raised walkways for the supervision of work, and ventilated roofs to deal with the noxious gases being produced. Abel also oversaw the expansion of the laboratory over subsequent decades and conducted important researches into guncotton, cordite and other explosives.

Another significant site was the King’s Observatory at Kew (listed Grade I). This building dates from the 1760s, but was taken over by the British Association for the Advancement of Science in 1842. It was used for meteorological, magnetic and astronomical research, but it also served a crucial function as a site for the testing and standardization of instruments. A comparable site is Alexander Strange’s observatory at Lambeth, established in 1865, which tested instruments used in colonial surveys. It was Strange whose 1868 provocative address to the British Association led to the creation of the ‘Devonshire Commission’, which studied questions of national provision for the sciences and led to increased government funding for scientific research. The fruits of this support paid off gradually: by the 1890s new institutions were founded, including the London School of Tropical Medicine (under the Colonial Office), the Jenner Institute (subsequently ‘Lister Institute’) for bacteriological research, and the Davy-Faraday Laboratory at the Royal Institution.

The Great Exhibition of 1851 is another useful marker of the changing status of science in Great Britain in the mid-nineteenth century. Just as the Exhibition was a demonstration of national success in industry, it also revealed the level of organized education on the continent, and was used in arguments over the integration of technical and scientific training with industry. Meanwhile, the pedagogical effects of 1851 were enormous. The most visible consequence was the development of South Kensington as a site of combined ‘Art and Science’ (bearing in mind the older usage of ‘art’ to mean something like ‘applied design’). The full vision for ‘Albertopolis’, as it was colloquially known, was only ever partly realized, but important institutions including the Natural History Museum, Royal College of Mines, Imperial Institute, Royal College of Science and the Central Institute were built in the 1870s and 1880s. Some of these buildings survive (Fig 4); by 1910 the Royal College of Mines, Imperial Institute, Royal College of Science and Central Institute had been consolidated as Imperial College.

The formation of the governmental Department of Science and Art (DSA) was also a direct consequence of the exhibition; this organization oversaw the development of practical teaching in the sciences in schools across the country. The key figure was the biologist Edward Frankland, who used the financial aid that could be granted by the DSA to force schools to construct buildings were dedicated to science teaching, and used the examination system administered by the DSA to emphasize practical instruction over textbook learning. Through the second half of the nineteenth century the number of school laboratories jumped from the low tens to the low thousands.

Although successful in its own right, the DSA's efforts were by no means as systematic or extensive as many wished, and further impetus to the question of scientific education was provided by the 1867 Paris 'Exposition Universelle', which was widely perceived as a disastrous failure for Great Britain. Through the 1870s and 1880s various attempts to begin a nationwide programme of technical education faltered, although pioneering technical colleges were built in London (Finsbury Technical College, 1883; The Central Institution, South Kensington, 1884–5), and Bristol (The Merchant Venturers' School, 1885). Two architects dominated this period of laboratory building: Alfred Waterhouse and Edward Cookworthy Robins, whose 1887 Technical School and College Building

Figure 4: The Royal College of Science, South Kensington; completed 1872.

provided the first systematic treatise on laboratory architecture in English. In 1889, a Government Technical Instruction Act was passed, leading to a programme of building through the 1890s.

In higher education, too, the sciences were taking hold. University College London already had good laboratory facilities in chemistry, to which physics was added in 1866, but the old universities of Oxford and Cambridge were also gradually catching up. A series of Royal Commissions placed increasing pressure on Oxbridge, and a new generation of reform-minded scientists effected change from within. Laboratories for chemistry were established in Oxford in 1860, and for physics in Oxford in 1870 and Cambridge in 1874. Laboratories were also opened at Bristol, Leeds, Liverpool, Sheffield, Birmingham, King's College London, and the Royal Naval College, Greenwich.

The history of the industrial laboratory cannot be clearly distinguished from the history given above: as mentioned, all early chemical laboratories had some commercial function. In addition, it is hard to classify the work of a scientist like William Henry Perkin, who made significant contributions to the dyestuffs industry from his apartment in Cable Street, London. This was not an 'industrial laboratory', yet it marked a decisive phase in the relationship between scientific research and industrial production, and was directly paralleled by more substantial interrelations between 'pure' and 'applied' science on the continent. A more recognizably modern industrial laboratory was in existence in Wolverhampton, as part of the manufactory of William Bailey and Son, who in 1861 leased a building referred to as a 'chloride of gold laboratory'. By the end of that decade laboratories are known to have been linked with breweries, alkali manufacturers, railway workshops and pharmaceutical firms. The practice of merely employing chemists – without necessarily providing them with laboratory facilities – remained common, however.

Finally, although the emphasis had shifted decisively to large-scale institutional training and research, this by no means signalled the end of the domestic laboratory. Important examples in the second half of the nineteenth century included Charles Darwin's personal laboratory at Down House (listed Grade I), and Lord Rayleigh's physics laboratory at Terling Place (listed Grade II*).

2 Development of the building type

The earliest laboratories, as we have seen, were simply workshop spaces or private rooms. Researches were carried out in alchemy, metallurgy, medicine, anatomy, natural philosophy and industrial chemistry. Andreas Libavius was amongst the first to set down the specific requirements of a laboratory, when he designed his 'chemical house' in 1606 – though this was in fact never constructed. Libavius' laboratory was distinctly urban, similar in style to merchants' houses in the German lands from the period (Fig 5). The interior layout is notable for its ambition: side rooms are provided for storage, and for certain special procedures. There is also a private laboratory, linked to a study and living quarters and separate from the main laboratory.

However, little is known of the internal layout and working conditions of early laboratories as they were actually built and used, and Libavius' design was more complex than any buildings actually in use until the nineteenth century. The most reliable early-modern illustrations we have depict metallurgical workshops, in which the basic functions of testing metals (assaying) were conducted. The defining feature of all early laboratories is the presence of one or more furnaces. This was both the most important element in the work being done, and also posed the biggest problems for laboratory design: the furnace both enabled and endangered the precise work of preparing and altering samples. A second notable feature of early laboratories is the presence of distilling apparatus, with which acids could be prepared.

Unlike Libavius' compartmentalized plan, early illustrations of laboratory interiors show a relatively large, undifferentiated space with little or no specialized furniture, aside from the instruments and tools themselves (Fig 6). Often these spaces were relegated to the basement, but this conflicted with the importance of windows for light and ventilation.

The basic arrangement of rooms – with a furnace or series of furnaces, fume hoods for ventilation, good sources of illumination and storage for apparatus – continued through the eighteenth century. When laboratories eventually emerged from the basement, they were modelled (like Libavius' prototype) on domestic architecture. The state-of-the-art in internal layout can be seen in the impressive illustration of William Lewis's laboratory at Kingston, Surrey, in use for his chemical researches from the late 1740s. (Fig 7).

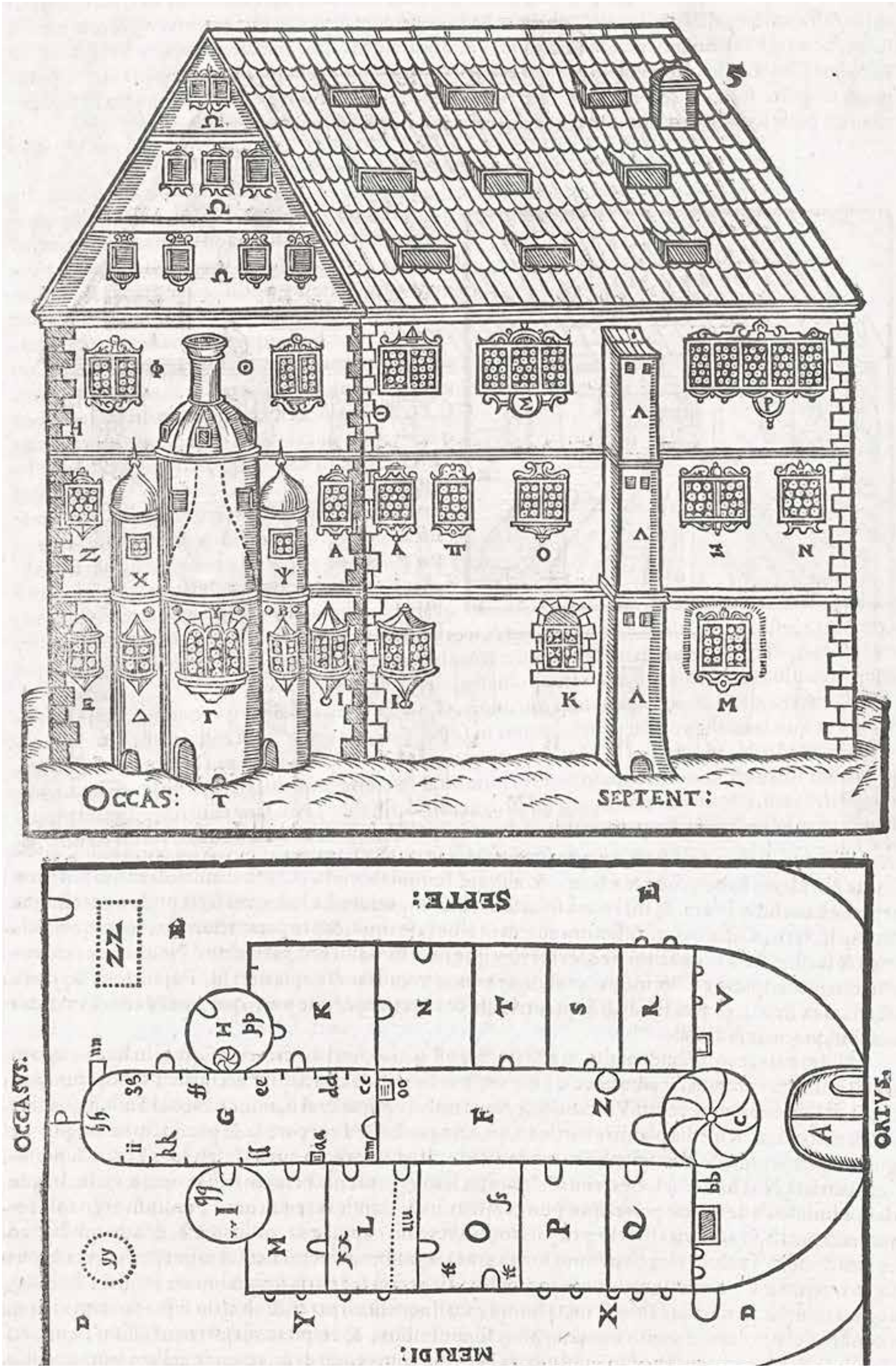

Figure 5: Elevation and groundplan of Libavius' chemical house, 1595. Key (from Owen Hannaway, 'Laboratory Design and the Aim of Science', in *Isis* vol 77 (1986), 585–610): A: East gate. [B]: Porticoed terrace (not marked, but presumably between gate and entrance to house). C: Spiral staircase to lower- and middle-level atria. D: Garden. E: Northern walkway. F: Lower atrium or vestibule of the laboratory. G: Laboratory. H: Adytum with spiral stair to study. I: Assay room tower. K: Storage room for chemicals. L: Preparation room. M: Laboratory assistants' bedroom. N: Apparatus storage room. 0: Coagulatorium. P: Wood storage room. Q: South storeroom. R: Vegetable storage room. S: Wash room or wood storage room. T: Room for undressing. V: Cellar for provisions. X: Wine cellar. Y: Laboratory cellar. [Z]: Aqueduct (not marked). aa: Entrance to laboratory cellar. bb: Entrance to wine cellar. cc: Steam bath. dd: Ash bath. ee: Simple water bath. ff: Downward distillation apparatus. gg: Sublimation apparatus. hh: Central hearth (*focus communis*). ii: Reverberatory furnace. kk: Stepped-down distillation apparatus. II: Serpentine distillation apparatus. mm: Dung bath. nn: Bellows. oo: Coal cellar. pp: Philosophical furnace. qq: Assay furnace. rr: Assay balance. ss: Vessels for coagulation. tt: Distillation using cloth fibers. uu: Press stand. xx: Desks, preparation tables, and mortars for grinding. yy: Fishpond. zz: Site for saltpeter, alum, and vitriol works.

Figure 6: Metallurgical laboratory, depicted by Lazarus Ercker, 1574.

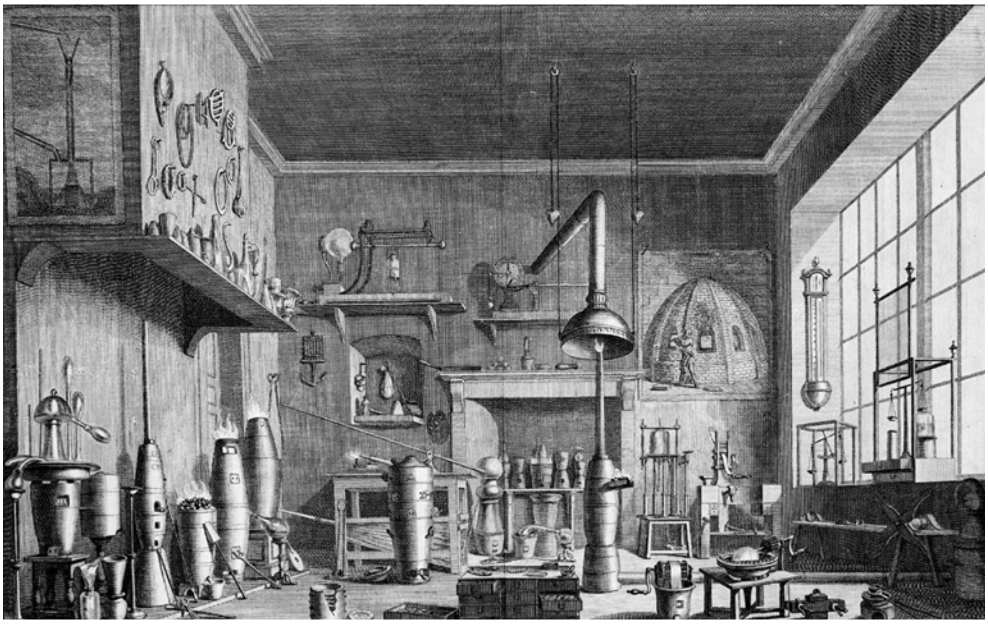

Figure 7: William Lewis' laboratory, Kingston, Surrey, 1763.

This was one of the most advanced laboratories of the mid-18th century. The fact that this engraving served as a frontispiece to Lewis's 1763 book *Commercium Philosophico-Technicum* was in and of itself a significant innovation, elevating a space associated with manual labour to the status of an emblem of 'useful knowledge', dedicated to none other than King George III. This was a space that is clearly purpose-built for chemical work, with large windows illuminating the apparatus (in particular the balances on the window-sills), a number of furnaces with two kinds of fume extraction (the conventional hearth on the left, and the novel fume hood in the centre of the engraving). We can also clearly see the lack of stable surfaces for precise work that would become important later, and the relatively small degree of separation of functions (furnaces on the left, balances on the right).

The laboratories of Lavoisier in Paris and at the Royal Institution in London show a new level of institutional support, and, crucially, a subtle but important shift in laboratory design (see Fig 3 above). No longer does the furnace dominate a room that is fitted out for the production of substances; now there is more attention given to table-top research and the storage of materials and instruments.

The Royal Institution, however, did not provide a model that could easily be imitated. The use of the laboratory for research was already relatively standard, and the limited teaching facilities were based on the model of practical demonstration, rather than hands-on instruction. Of far greater influence were the laboratories at University College, London (UCL) completed in 1846, and the laboratories designed by Wilhelm Hofmann at Bonn and Berlin in 1864. The latter, especially have been aptly termed 'chemical palaces' and established a new architectural scale for the laboratory.

The 'Birkbeck Laboratory' at UCL, meanwhile, offered a scheme for internal layout that could be imitated, with rows of desks running at right angles to the large windows (Fig. 8).

Figure 8: The 'Birkbeck Laboratory' at University College, London, 1846.

This was the first purposed built teaching laboratory in the country. It was designed by Thomas Donaldson, first professor of architecture at UCL, and was based on his observations of Liebig's laboratory at Giessen. Donaldson copied Liebig's crucial innovation: the central placement of tables. Now, more than twenty students could easily be accommodated – stretching to double that if necessary – working at long double-sided desks with integrated storage. The building was well-lit and had high ceilings to carry away fumes. Oversight of students' work was carried out by laboratory assistants patrolling the two rows between benches. All subsequent teaching laboratories owe a debt to this revolutionary design. When laboratories were adapted to accommodate the life sciences this arrangement was particularly useful, as it maximized the amount of light available to each student, now equipped with his or her own microscope.

Another subtler architectural transformation was the shift away from domestic models for laboratory buildings. For example when Cambridge's Cavendish Laboratory was completed, in 1874, the street-facing part of the building was inspired by neo-gothic country-house design, but the main group of research rooms, forming a courtyard at the rear of the building, were starkly functional, with tall windows allowing light into the optical research rooms, large window-sills to receive heliostats to guide beams of sunlight into the rooms, and a tower for a water pump that could evacuate air from vessels around the building (listed Grade II).

In terms of interior design, three inter-linked developments were central to the completion of the 'laboratory revolution'. First, laboratory furniture was increasingly specialized and began to form a key part of the architect's specification. The modern laboratory bench – with central divider and cupboards instead of table legs – has its origins in the 1840s, when examples can be seen in illustrations of the Pharmaceutical Society Laboratory (1844) and the Birkbeck Laboratory (1846; see Fig 8). The material of the chemical bench was given much thought, owing to the number of spillages and the nature of the liquids encountered – deal was generally preferred, though teak was used by those who could afford it (paraffin was was used as a sealant). Bottle racks are another important innovation of the nineteenth century, and can be seen in bookshelf form in the Royal Institution laboratory (see Fig 3). By the 1860s bottle racks were incorporated into the central divider of the laboratory bench. From the middle of the nineteenth century specialist furniture and apparatus can be found in the numerous trade catalogues of instrument-makers to the various scientific disciplines. Typically these original features do not survive *in situ*; nor are they commonly found in museum collections, which have tended to focus on instrumentation instead of furniture. Second, the fabric of the building was increasingly considered from a scientific point of view, both in terms of the function of equipment and the safety of laboratory workers. Early in the nineteenth century piped steam was introduced as a means of heating chemical apparatus, and by the end of the century electrical power was occasionally used (typically from local generators, but from mains supply at the Royal Institution as early as

1892). Ventilation, sanitization and drainage formed a focus of attention from the 1860s on, though exposure to dangerous substances remained little understood until well into the twentieth century. Third and finally, perhaps the most important innovation in terms of internal layout in the

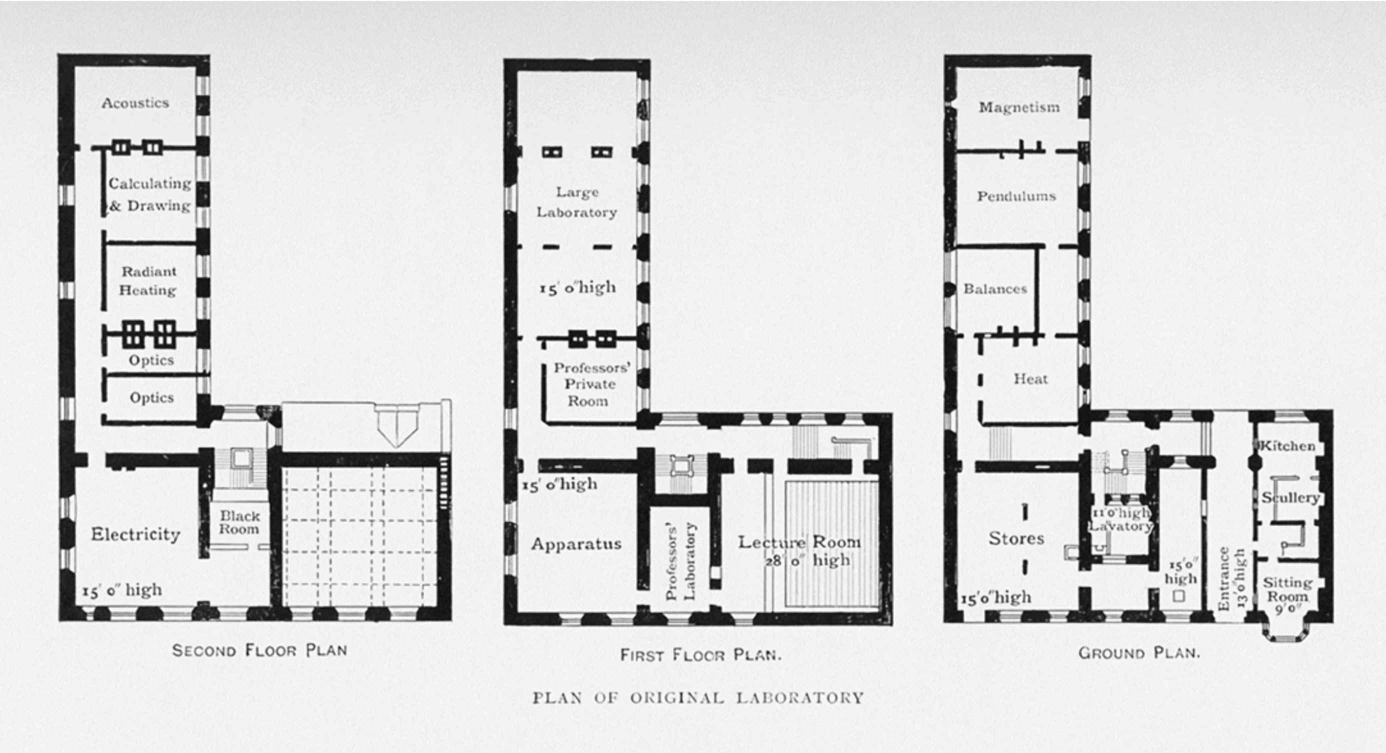

Figure 9: The internal layout of the Cavendish Laboratory (experimental physics), University of Cambridge, 1874. Maxwell brought about a minor revolution by grouping the rooms solely in relation to the kind of equipment they were to contain. Among other innovations, sensitive measuring apparatus was placed in special parts of rooms with pedestals sunk into the ground; a standard of length was built into the floor of one of the rooms; and the electrical room contained a custom-built de-humidifier.

late nineteenth century was the compartmentalization of functions, and the careful attention given to the relation of the fabric of the building to the increasingly sensitive equipment it contained. The Clarendon in Oxford and Cavendish were pioneering in this respect: James Clerk Maxwell at Cambridge combined attention to the physical aspects of the building with a revised layout, whereby rooms were organized not by sub-discipline but by instrument-type (Fig 9).

Specialization of function continued throughout the 1870s and 1880s: these decades saw the development of laboratories in disciplines that had been taught within the lecture hall or alongside museum specimens, including geology, zoology, botany and physiology. Often separate laboratories for a range of disciplines were contained in a single building; this was the model followed in the new technical schools, of which Finsbury Technical School was the first and most significant (Fig 10; listed Grade II). This building, finished in 1883, incorporated every possible innovation of the time. Ventilation flues, for example, were built directly into the chemical benches; these were evacuated through a main chimney exhausted by Argand lamps that also served to illuminate students' work.

In spite of all this advance in laboratory design, it is notable that the new laboratories at Leeds (1874), Aberystwyth (1872), Bangor (1884), Cardiff (1883), and Reading (1902) were all built within older buildings, including courts, hotels and hospitals. Another important point about laboratories in this period is that they often outgrew themselves, with work being carried on in out-buildings or rooms borrowed from other university departments. Another phenomenon that was in just as common around the turn of the twentieth century as it is now is the ability of laboratories to grow outwards from a central point. The National Physical Laboratory – an institute for the determination of physical standards – is a dramatic instance of this: the laboratory was founded in 1900 at the eighteenth-century Bushy House (listed Grade II*), first occupying the 22-acre grounds of the house, and then, by 1970, some 60 more acres in Teddington.

Figure 10: Finsbury Technical School, opened 1884 (now Shoreditch County Court).

3 Associations

From the beginning, laboratories brought natural inquiry into close contact with industrial production. The investigation and production of materials was primarily a commercial venture, and laboratory spaces were not distinct from industry. The history of the laboratory is also the history of the apothecary’s shop, the physic garden, the textile-manufacturer’s workshop, the miner’s assay rooms, the arsenal, the mint and even the brewery.

Another important association, which might at first seem contrary to the first, is with the domestic setting. Many laboratories, especially in the eighteenth century, were either set up in houses, were built in imitation of domestic architecture, or were adjacent to larger dwellings.

Finally, within the sciences it is important to acknowledge the often lowly or subordinate position of the laboratory, and its relation to other kinds of scientific space. The most significant of these is the museum. At the Ashmolean in the seventeenth century the laboratory occupied the basement, while the museum was located on the top floor; this was a symbolic as well as a practical arrangement. The laboratory was a place of manual labour – it was rough, earthy and perhaps even uncouth. The museum was an altogether more dignified place. This relationship persisted into the nineteenth century. When the sciences were developed institutionally at Cambridge and Oxford, museums took priority, with laboratories only following later. By the end of the nineteenth century the situation was changing rapidly. Yet even once the laboratory had become the pre-eminent place for scientific research, museums were still considered an important part of laboratory architecture. Owing to the gradual decline of even these smaller museum spaces, few if any of these laboratory museums have survived.

4 Change and the Future

Change is a constant in the history of scientific buildings. Laboratories in particular have often been victims of their own success. As soon as space for research or teaching is established it becomes inadequate, and adaptations are made or new spaces sought. Changes in techniques, instrumentation and the understanding of the relation between the physical environment and precise measurement have led to successive waves of construction and destruction of buildings. The survival rate for laboratories is extremely low, and none survive unaltered.

However, historians of science have been keen to emphasize that change and re-use are just as important as the moment of origin – this is true in the development of ideas and theories, the development and use of instruments, and it is certainly true in scientific architecture. This is an especially pressing issue at a time when the sciences have expanded to such a scale that older urban laboratories are deemed inadequate, and new locations are sought. Given the lack of knowledge about historic scientific buildings this leaves old laboratories especially vulnerable to demolition or radical overhaul.

In this IHA the emphasis has been placed on the development of laboratories as a part of the development of science as a series of institutions, in contrast to a history of science that emphasizes theoretical breakthroughs or discoveries. The point is that it is relatively easy to identify the 'place where X was discovered', but it is much harder to identify a building that is significant because of the kind of institutional prestige or foothold it gave to science. It is hoped that many more early laboratories will be identified, in particular domestic laboratories from the seventeenth and eighteenth centuries, school laboratories from the first half of the nineteenth century, and industrial or commercial spaces where research was carried out.

This notion remains important in post-1900 laboratories. The single most significant development after that date is the integration of specialized experimental research and laboratory design. For example, the Royal Society Mond Laboratory, part of the Cavendish Laboratory at the University of Cambridge, was designed in the early 1930s by the architect H. C. Hughes and the scientists Pyotr Kapitza and J. D. Cockcroft. Between them they came up with a solution to a large number of technical problems in Kapitza's research into low-temperature physics, and the result is a building that is as much a part of the experimental programme as the detection instruments it contained. At the other end of the scale, but no less functional, are standardized laboratories, especially those for schools and universities, that were built in large numbers, often following the templates laid down by E.C. Robins, in *Technical School and College Building* (1887) and Felix Clay, in *Modern School Buildings* (1903).

A final point, that serves to unite the entire history of the laboratory, is that scientific buildings cannot be considered apart from their surroundings: observatories need isolation and, since the nineteenth century have often been built at high altitudes; museums tend, by contrast, to be urban and public-facing. Laboratories require a degree of isolation, but have often been centrally located, in part owing to their dependence on sources of power and materials already present in urban centres. The proximity of certain specialisms to one another is another point to consider. Low temperature research and engineering departments can offer services to other laboratories, for example. Physics and chemistry can share tools and expertise. Finally, as more space is sought for the sciences, especially in physics and biotechnology, the entire shape of research is transformed. This presents challenges in identifying buildings left behind as researchers move away, and in identifying pioneering buildings on sites that become important only in a gradual and piecemeal way.

5 Further Reading

An essential introduction to the history of the chemical laboratory is Peter J.T. Morris' *The Matter Factory* (2015). This is the only monograph on the subject, but useful essays can be found in the *Oxford Companion to the History of Modern Science* (2003), *The Cambridge History of Science* (vol 3, 2008), and *A Companion to the History of Science* (2016). Essay collections with useful background are Frank James (ed.), *The Development of the Laboratory: Essays on the Place of Experiment in Industrial Civilization* (1989), Peter Galison and Emily Thompson (eds), *The Architecture of Science* (1999), and Crosbie Smith and Jon Agar (eds), *Making Space for Science: Territorial Themes in the Shaping of Knowledge* (1998). An important essay on early laboratories is Owen Hannaway's 'Laboratory Design and the Aim of Science: Andreas Libavius versus Tycho Brahe', in *Isis* vol 77 (1986), 585–610. For the place of experiment at the time of the founding of the Royal Society see Stephen Shapin, 'The House of Experiment in Seventeenth-Century England', in *Isis* vol 79 (1988), 373–404.

Further information on chemistry laboratories can be found in the essays of William H. Brock, in particular 'British School Chemistry Laboratories, 1830–1920', in *Ambix* vol 64 (2017), 43–65. The historian most consistently concerned with scientific architecture is Sophie Forgan, whose essays on university architecture, and (with Graeme Gooday) the sciences at South Kensington are invaluable. Also useful is Gooday's essay 'Precision Measurement and the Genesis of Physics Teaching Laboratories in Victorian Britain', in *The British Journal for the History of Science* vol 23 (1990) 25–51. There is an extensive literature on technical education; a useful introduction is given on the website *Technical Education Matters*: technicaleducationmatters.org. For the history of laboratories for gunpowder manufacture see Wayne Cocroft, *Dangerous Energy: The Archaeology of Gunpowder and Military Explosives Manufacture* (2000). Many individual laboratories and institutions have their own histories, in particular the National Physical Laboratory, the University of Oxford, and the Cavendish Laboratory, Cambridge.

The key primary source for Victorian laboratory architecture is E.C. Robins, *Technical School and College Building* (1887). Standards for school laboratory building at the beginning of the twentieth century were set by Felix Clay's *Modern School Buildings* (1903), chapter VIII.

6 Acknowledgments

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