THE LABORATORY

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Suggested Citation: Henning Schmidgen, "The Laboratory," *Encyclopedia of the History of Science* (April 2021) doi: 10.34758/sz06-t975

It is almost impossible to imagine science without laboratories.[1] Our concept and image of modern science is fundamentally defined by special buildings in which experts utilize vast technical resources to investigate natural phenomena and processes. An entire iconography exists, depicting the laboratory scientist in the midst of extremely complex and precise instruments examining an object in his hand or looking at a brightly illuminated screen.

However, the notion of the laboratory on which this iconography is based is being called into question by current developments in scientific practice. In particular, the massive research centres for particle physics, such as Fermilab near Chicago or CERN in Geneva, and the large scientific projects of recent biological research, such as the Human Genome Project, have contributed to the expansion of the laboratory into a network and its extension far beyond the confines of the natural sciences. Enhanced by the process of digitization these developments have led to a state of things in which the laboratory bears little resemblance to the traditional image of table-top experiments in an enclosed space. Nonetheless, there is no doubt that the architecturally delimited laboratory – like the factory, the railway station or the department store – is an exemplary site of modernity.[2]

During the last third of the 19th century in particular, specially designed and equipped buildings became central institutions of scientific endeavour. Being involved in this endeavor no longer meant striving for the formation of individual knowledge and personality, as was the case in the Romantic period. To the contrary, work in modern laboratories was increasingly carried out by "disenchanted" professionals who applied professional methods for creating innovations. As the workplace of the chemist, the physicist and the biologist – and subsequently also of other specialists, such as the psychologist, the linguist and the archaeologist, for example – the laboratory was transformed in this period to a space of knowledge which primarily served to establish new scientific facts.

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1 This article is a revised, updated and expanded version of my contribution to "EGO – European History Online." I thank Hartmut Trischler, Lisa Landes, and Niall Williams for her help in establishing this earlier version. I thank Christopher Phillips for his insistence and assistance in preparing the present article.

2 Galison and Jones, "Factory, Laboratory, Studio," 497–540.

This special form of knowledge production was increasingly subjected to an economic regime which was guided by the principles of specialization, mechanization and standardization. In the laboratory, the activities of the scientist assumed some of the characteristics of work at the conveyor belt. According to the frequently repeated expectation – and in some cases the fears of contemporaries – novel facts could now be produced "by the dozen" in the laboratory.[3]

It is not surprising, therefore, that the laboratory incorporates and reflects the often contradictory tendencies of an increasingly industrialized society. Like a metropolis in miniature, the laboratory was a site where combinations and confrontations of human and machine, body and technology, organisms and instruments occurred. The effects of these multiple conjunctions and disjunctions were registered, measured and calculated, they were represented, published and publicized and demonstrated in front of large audiences.

The multifarious materials of the laboratory environment and its components constituted a counterpoint to the idealism of scientific insights, categories and values, and the increasingly divided nature of the research process contrasted with the ascription of discoveries and achievements to individuals – on the level of individual people, but also on the level of nations.

The routinization of work processes continuously conflicted with the principle of being open to the unexpected, a principle which is particularly characteristic of the activity of the modern scientist. Scientific practice became work in the sense of labor. At the same time, however, scientists had to be ever prepared to break with their routines in order to allow time and space for new and surprising developments. Thus, in the context of a society which regarded itself as progressive, the laboratory can be viewed as one of the sites where that society is "condensed." This applies to the production of that which is new, but also with regard to the problem of its representation – in particular since the computer and similar information technologies have became key components of laboratory work.[4]

It is therefore astonishing that a comprehensive history of the laboratory has not yet been produced. As a consequence, a comparative history dealing with different national and cultural traditions of laboratory research or local aspects of the "laboratory revolution" in different disciplines is nowhere in sight. Not even overviews regarding the history of the laboratory such as exist for other spaces of knowledge – like the clinic or the observatory – have been produced.[5]

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3 See Weber, "Wissenschaft als Beruf," as well as more recently Paul Rabinow, *Making PCR*, and Steven Shapin, *The Scientific Life*.

4 Knorr-Cetina, "Das naturwissenschaftliche Labor," as well as Bruno Latour, "Give Me a Laboratory and I Will Raise the World."

5 See, for example, Foucault, *The Birth of the Clinic*, and Donnelly, *A Short History of Observatories*.

It is true that the interest in researching day-to-day life in laboratories from an ethnological perspective, which has primarily been awakened by recent trends in the sociology of scientific knowledge,[6] has in recent years prompted a number of science historians to focus on individual laboratories. For example, Timothy Lenoir, Sven Dierig and Daniel Todes have published detailed studies concerning the history of physiological laboratories in Leipzig, Berlin and St. Petersburg, whereas Peter Morris has authored a comprehensive account covering the emergence and evolution of chemical laboratories.[7]

Relevant information about the founding and expansion of laboratories in individual national contexts has also been collected for specific disciplines, for example by David Cahan for physics in the German-speaking territories. Peter Galison has reconstructed the “material culture,” including laboratory architecture, of 20th-century microphysics in the United States, while Robert Kohler did something similar – though less comprehensively – for the history of ecology, ethology and evolutionary biology in the US. Thus far, however, no overall picture emerges from these contributions.[8]

While these studies are quite varied, they often attempt to draw analogies between the laboratory and the factory, or between the scientification and industrialization, without expressly allowing room for highlighting differences between research and labor. One of the consequences is that the aspect of production is emphasized above the aspect of representation in a way which seems not entirely justified by historical events. Viewed from a perspective of historical proximity, the laboratory has never just been a space of knowledge *production*; it has also always been a place of representing, recording, and calculating. Conversely, it seems inappropriate to conceive of the laboratory as a writing space, even if or perhaps precisely because the increasing use of computer technologies suggests this notion. The modernity of the laboratory resides in the very fact that it embraces both aspects, i.e. production *and* representation.

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6 The key reference in this connection is obviously Latour and Woolgar, *Laboratory Life*. Already in 1936 the Norwegian philosopher Arne Naess had suggested that the actions of scientists, both verbal and nonverbal, could be described using the methods of behavioral science; that is, they should be observed as though by a “researcher from a different galaxy.” See Naess, *Erkenntnis und wissenschaftliches*, 9. However, only the work of the sociologist Stewart E. Perry, who in the 1960s observed the scientific practices of medical practitioners in a psychiatric clinic, and the studies on From Anxiety to Method in the Behavioral Sciences published by the French-American ethnologist and psychoanalyst Georges Devereux in 1967 actually went in this direction. See Perry, *The Human Nature of Science*, and Devereux, *From Anxiety to Method in the Behavioral Sciences*. On the parallels between Perry and Latour see Westrum, Review of *Laboratory Life* and *The Human Nature of Science*.

7 Lenoir, *Instituting Science*; Dierig, *Wissenschaft in der Maschinenstadt*; Todes, *Pavlov's Physiology Factory*; and Morris, *The Matter Factory*.

8 Cahan, *Meister der Messung*; Galison, *Image and Logic*; and Kohler, *Landscapes and Labscapes*. See also James (ed.), *The Development of the Laboratory*. For an overview concerning historical studies of laboratories see Kohler, “Lab History: Reflections,” as well as the subsequent contributions in that issue by Klein, Gooday and Gieryn.

The knowledge of and about laboratories has a history of its own. Before sociologists and historians of science got interested in the laboratory, the scientists themselves turned their attention to these specific institutions, followed shortly by politicians and architects. The knowledge of and about laboratories consequently continues to depend on drawings, plan and other forms of pictorial representations. For the historian, this fact continues to represent a challenge, requiring them to take into account the iconography of the laboratory and its architectural form as the activities that take place within its walls. Doing so enables the hsitory of the laboratory to be closely linked with the history of modernity itself.

LABORATORIES IN THE EARLY MODERN PERIOD

The Latin term *laboratorium* (from the Latin term *labor*, meaning exertion, effort or work) was already in use in the medieval period. However, it was only in the late-16th century that the term assumed the meaning which it retains – in modified form – in modern languages today. In the 14th century, the term *laboratorium* meant simply a task or work. Around 1450, the first usages of the term relating to workshops can be detected in the context of monasteries. The term was apparently used parallel to terms such as *scriptorium* (copying room for scribes in medieval monasteries) and *dormitorium* (dormitory). In the 16th century, *laboratorium* primarily denoted workshops of alchemists, apothecaries and metallurgists, and subsequently came to refer to all accommodation in which natural phenomena and processes were explored by means of tools and instruments.[9]

The modern generalization of the term "laboratory," with its focus on science, only occurred around the turn of the 20th century. As defined in the German encyclopedia *Brockhaus*, for example, in present-day German the term describes a "workspace for scientific and technical experiments, measurements, evaluation tasks, controls, etc., with the furnishings and equipment required for these tasks." In a similarly general fashion, the current *Oxford English Dictionary* defines "laboratory" as a "building set apart for conducting practical investigations in natural science."[10]

Due to the focus on gaining knowledge by practical and material means, the history of the laboratory should be regarded as closely connected to the history of the anatomical theatre, of the cabinet of curiosities, of botanical gardens, of the observatory, and of similar spaces of knowledge. One of the first laboratories for which detailed information exists was housed in Uraniborg, the research centre which was built and equipped in the late-16th century for the Danish astronomer Tycho Brahe (1546–1601). Brahe's castle-like building on the island of Ven in the Öresund was divided into three parts: The upper floor contained astronomical equipment and was used for observing the sky; underneath this was the mathematical

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9 Hannaway, "Laboratory Design and the Aim of Science," 585. On the historical terminological see also Klein, "Die technowissenschaftlichen Laboratorien."

10 See *Brockhaus Enzyklopädie., Bd. 12*, 670, and *Oxford English Dictionary, vol. 8*, 558.

laboratory with tables for maps and calculations; and the cellar contained the laboratory of the alchemist (fig. 1).

Gestures of pointing up to the sky and taking notes down on a table connect these three levels. In fact, the spatial division and arrangement of the entire laboratory reflected Brahe's basic assumption that the microcosm and the macrocosm correspond to one another: "By looking up, I see downwards; by looking down, I see upwards." Astronomy corresponded with alchemy and vice versa, though the particular type of alchemistic activity involved was not specified.[11]

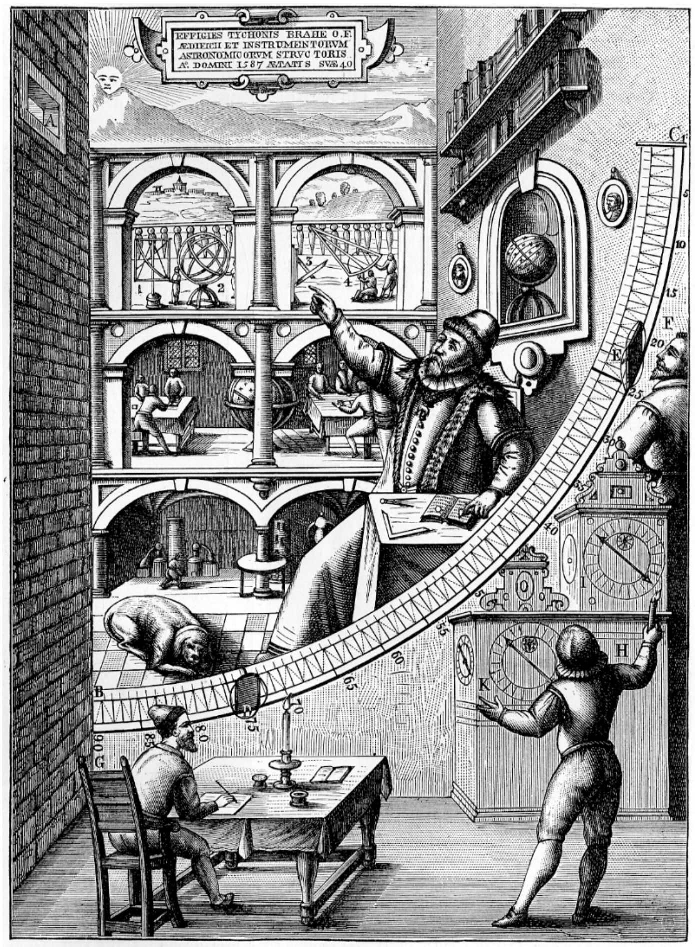

Figure 1: The wall quadrant in Uraniborg, 1909. Source: *Meyers Großes Konversationslexikon*, 6th edition, Leipzig 1909, vol. 2, p.111.

There are no explicit references to astronomy in the engravings and woodcuts from the 16th century depicting laboratories. In the case of Hans Weiditz (ca. 1500–1536), for example, or Pieter Breugel the Elder (1525/1530–1569), the laboratory appears as a jumbled workspace around which numerous vessels and instruments are strewn. In the midst of like-minded

11 Hannaway, "Laboratory Design," 598–609.

colleagues, the alchemist goes to work at a fireplace with his bellows, test tube and similar devices in a manner which remains vague (fig. 2).[12] In contrast, the depiction of Brahe, and also of the chemists' house of Andreas Libavius (1555–1616), show spacious accommodations in which the instruments are place in an orderly fashion, as though waiting to be used in a precisely controlled manner.[13]

Figure 2: Hans Weiditz (ca. 1500–1536), Two alchemists in the laboratory, wood engraving, 1532. Reproduced from: Staatliche Kunstsammlungen Dresden, Kuperstichkabinett.

An image from the same period depicts the basic components of the alchemistic laboratory which Count Wolfgang II von Hohenlohe (1546–1610) had constructed at Weickersheim Castle (fig. 3). Similar to Weiditz and Brueghel, Paul van der Doort (around 1600) depicts a fireplace with a vent in this copper engraving, but he arranges the test tubes and other vessels neatly on ledges, shelves and window-sills. Also, the alchemist is not at work handling equipment in this depiction. Instead, he is facing the books in a respectful pose.[14]

12 Hill, "The Iconography of the Laboratory."

13 On Libavius, see Hannaway, "Laboratory Design," 593.

14 On this point, see Smith, "Laboratories," 290–293.

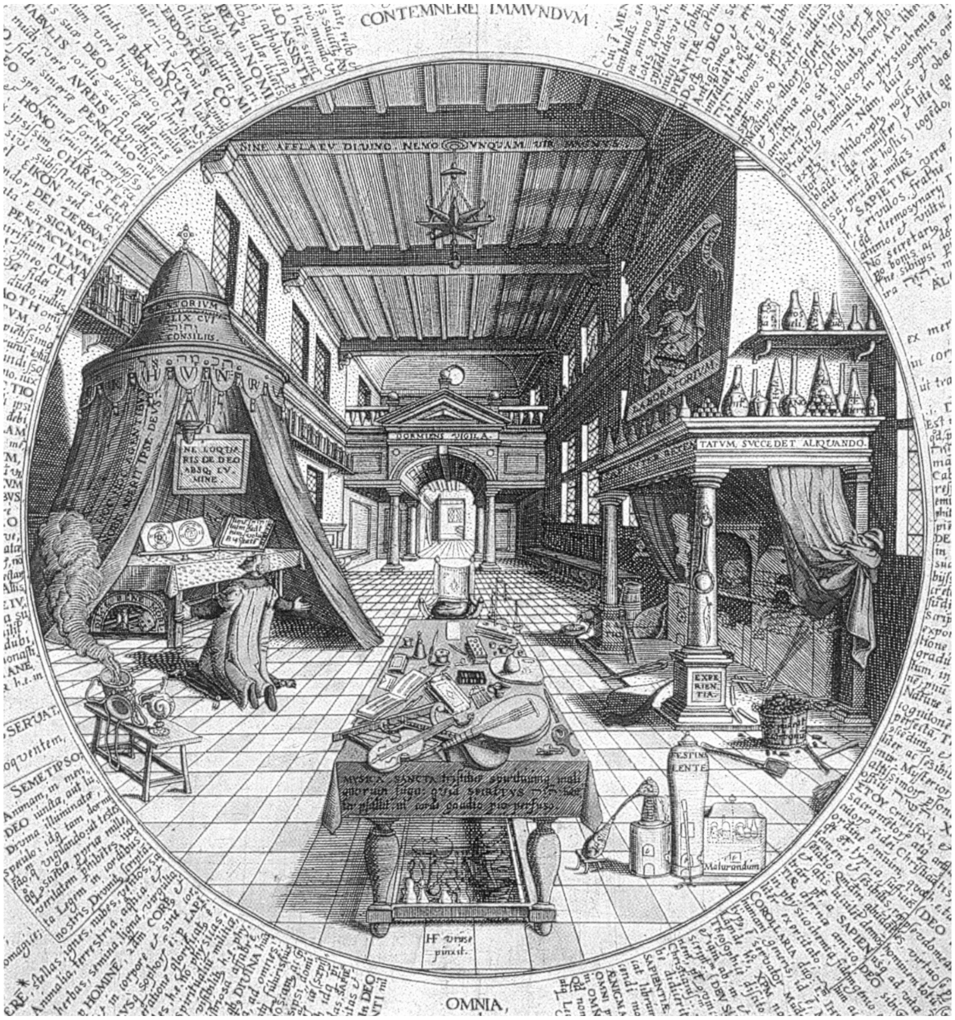

Figure 3: Paul van den Doort, The laboratory of the alchemist, copperplate engraving, 1609. Reproduced from: www.gallica.bnf.fr, <http://gallica.bnf.fr/ark:/12148/btv1b84185150/f1>.

Similarly arranged – though not as bright or as neat – are the paintings of David Teniers the Younger (ca. 1610–1690), who painted the motif of the "Alchemist in the Laboratory" in multiple variations during the 17th century. However, the depictions in these paintings are highly conventionalized and owe more to the genre paintings and still lifes on which they were based than to the reality of contemporary laboratories.[15]

Around the end of the 17th century, the laboratory of the alchemist became the first anchor point for a new type of science. The aim of this science was to discover useful facts about nature by concrete actions and, in doing so, to contribute to a renewal of the world. Francis

15 Hill, "The Iconography of the Laboratory." On Teniers, see Shapin, "The House of Experiment in Seventeenth-Century England," 379.

Bacon (1561–1626) and Robert Boyle (1627–1691) promoted the view that human craft should “challenge” nature, in order to “subjugate” it for the sake of truth and usefulness. Boyle in particular, who conducted experiments in chemistry and physics in his own laboratory, established a practice in which experiments were performed before a learned audience and were then published in a manner designed to be easily understandable so that others could repeat them. This new, active and experimental method of "philosophizing" was also the aim of the first scientific academies: the Academia dei Lincei in Rome (1603), the Academia Naturae Curiosorum (later Leopoldina) in Schweinfurt (1652), and the Royal Society in London (1660).[16]

There was a good reason why the early iconography of the laboratory frequently displayed books along with instruments. This visual representation of a new synthesis of manual and textual knowledge defined the laboratory not only as a place of manual work, but also as a space of reading, writing and calculating. Workshops as such had existed for a long time. However, the intention to use such spaces to establish scientific facts by means of physical activity – be it by manipulating material or using instruments – as well as to record these facts and to publish them, was new, as historian Pamela Smith concluded in 2006: “This interaction between scholarly and artisanal cultures during the Renaissance is the most important source for the transformation of values that led to the legitimation of bodily labor in a specially designed space as a means of producing scientific knowledge.”[17] Indeed, one could say that it was only through this interdependency of science, handicraft and text that the term “laboratory” received its ultimate meaning: the production site of scientific knowledge.

Be that as it may, even in the late-18th century this concept of laboratory had still not gained dominance. In spite of developments in chemical science – driven in particular by Antoine Lavoisier (1743–1794) – the laboratory remained primarily a workshop, a place of material productions. Even in the 1770s, the perception of the laboratory focused on the aspect of an increasingly rationalized activity in the developing area of chemical production.

Thus, the laboratory is described in the *Encyclopaedia Britannica* (1771) as “the chemist's work-house,” as the place where pharmacists and pyrotechnicians do their work.[18] The *Encyclopédie* (1765) of Denis Diderot (1713–1784) and Jean-Baptiste le Rond d’Alembert (1717–1783) defines the term in a similar way as an “enclosed and covered place, room, part of a house or shop which contains all chemical utensils included under the terms *ovens*, *vessels* and *instruments*, and in which chemical activities can be readily performed.”[19]

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16 On Boyle, see Shapin and Schaffer, *Leviathan and the Air-Pump*.

17 Smith, “Laboratories,” 296.

18 *Encyclopaedia Britannica*, 857.

19 *Encyclopédie*, 145 (italics in the original).

However, the accompanying illustration enriched the iconography of the laboratory by adding a new aspect: the organized division of labour. As in previous depictions, the room is dominated by a fireplace and a vent hood (fig. 4). The bellows for the smiths is also reminiscent of considerably older images of alchemists by Weiditz and Brueghel, and the ledge of the chimney contains a carefully arranged row of vessels, some of which had already been used for alchemy. At the same time, the room is populated by a collective which appears as strikingly modern. Its members perform different tasks at different positions in the room: a chemist sitting at the table discusses the production of solutions with a physicist; on the left, a laboratory assistant brings coal from the cellar; and on the right, another laboratory assistant washes vessels. This is the first depiction of a laboratory which includes a principle of organisation that would subsequently become a fundamental aspect of scientific laboratories in the modern period.

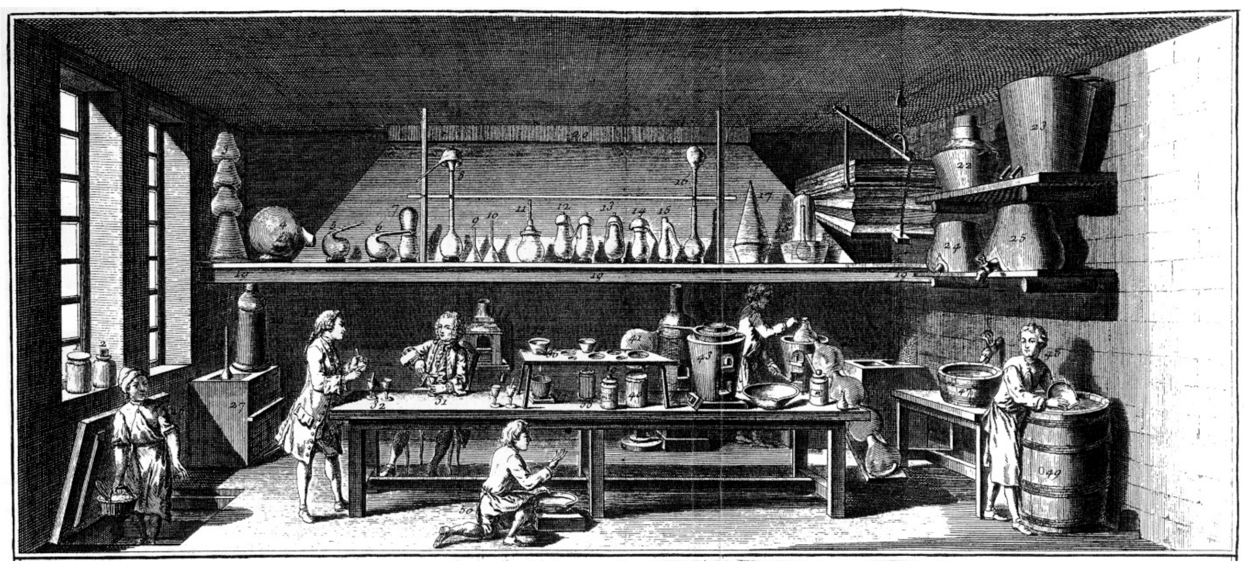

Figure 4: Chemical laboratory, 1765, unknown artist. Reproduced from: *Encyclopédie, ou Dictionnaire Raisonné des Sciences, des Arts et des Métiers*, Planches, Neuchatel 1765, vol. 33, "Chimie," Figure I.

THE LABORATORY REVOLUTION OF THE 19TH CENTURY

In the early-19th century, there were two factors driving the development of the laboratory. Firstly, the reform of existing universities and the founding of new universities was an important stimulus. After 1800, universities were no longer only places for the collection and ordering of knowledge; they increasingly became places of scientific and technical research. Of fundamental importance in this context was the foundation of the Friedrich Wilhelm University in Berlin (1810), which quickly attained international renown. Secondly – and more importantly – the success of individual private teaching and research laboratories contributed to a dynamically expanding and widely distributed system of laboratories. Initially set up and directed by highly motivated university teachers on their own initiative, some of these private laboratories quickly became integrated into the reformed universities.

A typical example of this is again a chemical laboratory: namely the one set up by Justus Liebig (1803–1873) in the 1820s at his home university in Gießen after returning from a research trip to Paris. Liebig's laboratory was a prime example of the endeavour to establish comprehensive instruction based on experiments, in which there was no longer a contradiction between science and handicraft. Indeed both were now complementary aspects of a single activity whose primary goal was the gaining and transmission of knowledge. A famous drawing by Wilhelm Trautschold (1815–1877) and Hugo von Ritgen (1811–1889) shows Liebig's laboratory as it would have looked at the beginning of the 1840s. With their "Interior View of the Analytical Laboratory in Gießen," Trautschold and von Ritgen show for the first time the laboratory as a vibrant place of teaching. They break with the static orderliness of the *Encyclopédie* and show a space where students and teachers from various countries work as a collective (fig. 5).[20]

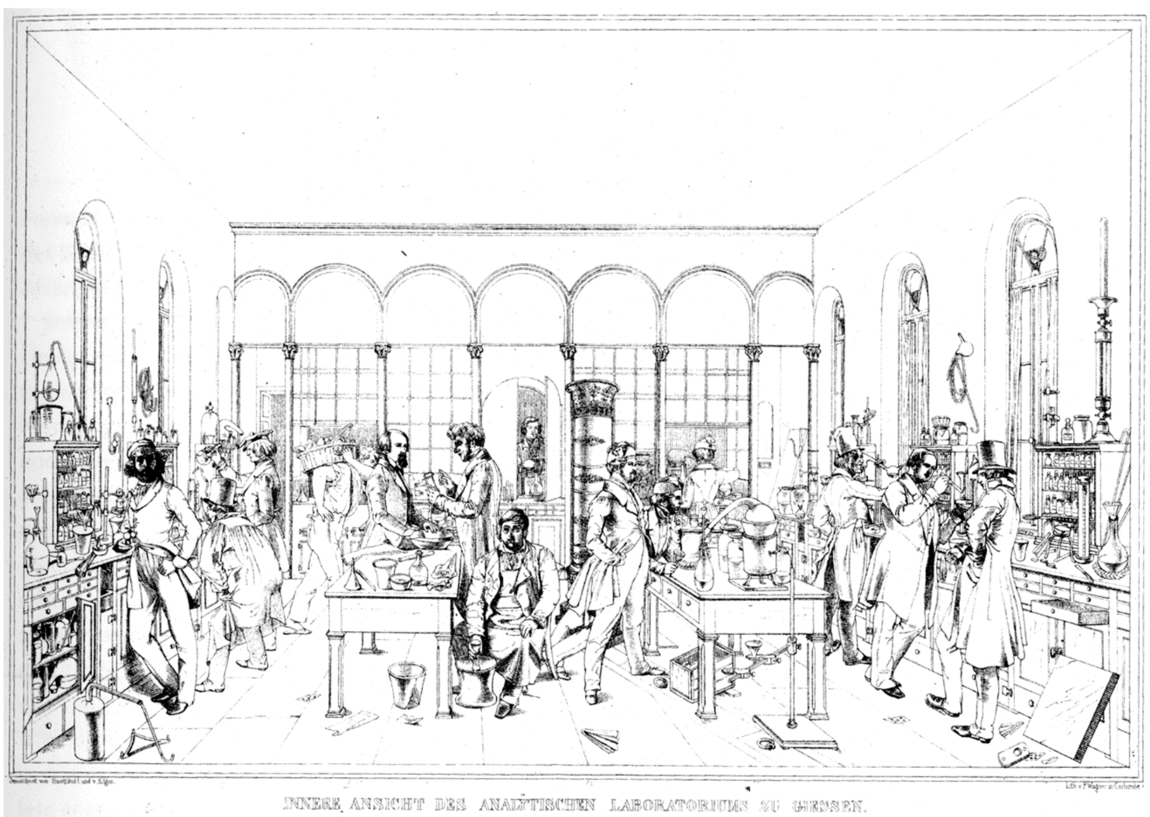

Figure 5: Interior View of the Analytical Laboratory in Gießen, lithograph, 1842, from a drawing by Wilhelm Trautschold (1815–1877) and Hugo von Ritgen (1811–1889). Reproduced from: J. P. Hofmann, *Das chemische Laboratorium der Ludwigs-Universität zu Gießen*, Tafeln, Heidelberg 1842, table VII.

20 On this point see also Klein, *Experiments, Models, Paper Tools*, 41–85. On Liebig, see Brock, *Justus von Liebig*.

Significantly, instead of Liebig himself, the laboratory assistant who, among other things, was responsible for supplying the basic chemicals and the glass and porcelain vessels, is at the centre of the drawing. The principle of the division of labour is also reaffirmed and highlighted. The laboratory does not only appear as a workshop or factory, but also as a kind of exchange or transit point of discourses, concepts and recipes, where ideas and physical materials could be confronted with each other and combined in increasingly new ways.

In addition, one of Liebig's interior architectural innovations is shown in the drawing. In older laboratories, the experimentation tables were usually placed against the wall, with one free-standing table placed in the centre. Liebig's contribution to the rearrangement of the laboratory was to distribute the experimentation tables throughout the entire room. This arrangement meant that more students could be accommodated and more experiments could be performed simultaneously, while the laboratory director still had a good overview and could easily move from one table to the next.[21]

Building on Liebig's groundwork, the establishment of modern chemistry in the German-speaking territories is regarded as one of the success stories of science in the 19th century. In the 1860s, completely new institutes for chemistry came into existence in Bonn, Berlin and elsewhere. These were quickly recognized throughout Europe as being exemplary with regard to their exterior and interior architecture, as well as their technical equipment.[22]

Somewhat earlier, around 1850, another teaching and research laboratory for chemistry was established in Heidelberg under the direction of Robert Bunsen (1811–1899). It led development internationally, not least because teaching there was enriched by impressive demonstrations of experiments. In addition to the rooms for work and practise, the weighing room, the stores and the library, the lecture theatre together with its preparation chamber at the back became thus an important component of laboratory buildings. In other words, the laboratory was not only longer a research site, it also became a space for teaching, a demonstration room and experimental theater.

The laboratory revolution occurred somewhat later in other disciplines. The first physics laboratory in the modern sense of the word was opened in 1833 by Wilhelm Weber (1804–1891) at Göttingen University. Previously, only physics "cabinets" had existed, that is, individual rooms in which collections of instruments were kept. In 1843, Heinrich Gustav Magnus (1802–1870) set up a physics laboratory in Berlin. Franz Neumann (1798–1895) followed suit in Königsberg in 1847. However, both were "private laboratories which were located in the living accommodation of the founders and were thus only accessible to others with the special permission of the founders."[23]

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21 Forgan, "The Architecture of Science," 424.

22 Forgan, "The Architecture of Science," 422.

23 Cahan, *Meister der Messung*, 6.

Only in 1846 was a (teaching) laboratory opened at Heidelberg University. In 1874, a newly built physics laboratory was completed in Leipzig. In subsequent years, similar teaching and research laboratories followed in Berlin (1878), Würzburg (1879) and Strasbourg (1882). The *Technisch Physikalische Reichsanstalt* opened in Berlin in 1887 and remained the biggest laboratory complex for engineering and physical fundamental research in the world up to the First World War.

The laboratory revolution took a similar path in another important area of science in the 19th century: the experimental life sciences, in particular physiology. The first physiological laboratory in the German-speaking territories was the institute in Breslau, which Jan Purkinje (1787–1869) officially directed starting in 1839. Inspired by the sensualistic pedagogy of Johan Heinrich Pestalozzi (1746–1827), Purkinje practiced a form of experimentation teaching based on *Anschauung* ("visual perception"). However, until the 1870s, this ideal was only rarely put into practice due to a lack of appropriately equipped physiological teaching and research laboratories, as well as the cost of the appropriate instruments.

Thus, the institute of Johanns Müller (1801–1858), which produced many important physiologists of the 19th century, prescribed participation in practical experiments in physiology, but could not provide the instruments required for this purpose. Instead, the students themselves had to make or buy them, and bring them to class. Around 1850 it was not at all uncommon for physiologists such as Theodor Schwann (1810–1882), Emil du Bois-Reymond (1818-1896) or Hermann von Helmholtz (1821-1894) to experiment at home or in a hotel room.

Modern laboratories for physiology only came into being later: in 1869 in Leipzig, in 1872 in Utrecht, in 1877 in Budapest and Berlin, in 1885 in Strasbourg, and so on. The importance of demonstration lectures for the teaching of experimental knowledge is demonstrated by the fact that Johann N. Czermak (1828–1873), a former student of Purkinje, had a *spectatorium* erected at his own expense for the teaching of physiology in the early 1870s in Leipzig. This *spectatorium* had a large auditorium specifically designed for demonstration experiments. Subsequently, it served as an example for the building of similar 'viewing theatres' at university institutes.[24]

It is only in the context of these developments, i.e., the emergence – particularly in the German-speaking territories – of specific laboratory cultures in chemistry, physics and physiology, that the term "laboratory" acquired the breadth of meaning which we are familiar with today. In the dictionaries and encyclopaedias of the 19th century, "laboratory" is almost universally equated with "chemical laboratory." This prevailing definition was only revised in

24 See Cunningham and Williams (eds.), *The Laboratory Revolution in Medicine*, and, with respect to the Spectatorium, Schmidgen, "Pictures, Preparations, and Living Processes," as well as Schmidgen, "1900 – The Spectatorium."

1898 when the expression was described as "generally" applying to a room "in which chemical, pharmaceutical, physical or technical work is performed."[25]

The iconography of the laboratory had also changed noticeably by that time. On the one hand, the laboratory appears as the background in paintings depicting eminent scientists, such as Louis Pasteur (1822–1895), as geniuses working largely alone, thereby harking back to earlier depictions of alchemists. On the other hand, laboratories appear as anonymous architectural plans and photographs of interior rooms which are usually empty of people. At this point, the tension between the scientific work performed by bourgeois individuals and anonymous masses becomes tangible.

From the 1870s, detailed descriptions of laboratories also appeared in scientific journals. Generally, such descriptions were produced by the directors of the institutions in question. Besides floor plans, such descriptions often presented various views, cross-sections and drawings of individual details such as experimentation tables, cupboards or darkening facilities in the lecture theatre. From the end of the 1880s, similar depictions can also be found in construction journals and architecture handbooks.

During the same period the laboratory begins to extend itself from the natural sciences to other branches of scientific work, in particular the humanities. The starting point is a disciplinary neighbor to physiology, namely psychology. As one of the firsts of its kind, the Leipzig Institute for Experimental Psychology was founded in 1874 and quickly gained international reputation. Its founding director, Wilhelm Wundt (1832–1920), a former student of du Bois-Reymond (as well as former assistant to Helmholtz), trained entire generations of experimental psychologists from all over the world. Once returned to their countries of origin, these "new" psychologists founded their own laboratories, for example Stanley Hall (1881 in Baltimore, Johns Hopkins University), James McKeen Cattell (1887 in Pennsylvania, 1890 in New York, Columbia University) or James Baldwin (1893, Princeton University). The new psychological laboratories in Paris (Beaunis, Binet) and Geneva (Flournoy) also adopted the Wundtian model, while modifying it according to their specific interests and issues.[26]

Equally in the 1870s, linguistics, or the science of language, turned away from being an endeavor exclusively based on systematic and historical-comparative investigations and gradually began to redefine itself as a laboratory science. When in 1897 the Collège de France opened a Laboratory for Experimental Phonetics, its director, Michel Bréal, declared his firm expectation that the scientific study of language will make great progress by using experimental methods.[27]

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25 *Brockhaus' Konversations-Lexikon Bd. 10*, 1989.

26 As an overview, see Schmidgen, *Hirn und Zeit*.

27 Gessinger, *Auge & Ohr*, and Brain, "Semiotics and Semiotics."

At about the same time, experimental aesthetics emerges as a new field of inquiry. Promoted by influential figures such as physiological psychologist Charles Henry (1859–1926), it quickly impacted on the arts, in particular the "pointillist" paintings of Georges Seurat. When in 1919, the Bauhaus was founded in Germany, this school of arts and architecture conceived of itself as an experimental site. The Bauhaus was devoted to the method of "laboratory work," which also led to establishing an "experimental theater" (*Versuchsbühne*) and the construction of "experimental homes" (*Versuchshäuser*).[28] The expansion of the notion of laboratory from alchemical work-house to general site of technical and scientific production was effectively complete.

LABORATORIES AND THE MOVEMENT OF PEOPLE BETWEEN THEM

Since the 1880s, knowledge of and about laboratories was increasingly disseminated by construction journals and architecture manuals. However, drawings and plans did not represent the only source of such knowledge: in particular, travel – study trips as well as research trips – served to spread it.

In fact, besides articles and books, it was primarily visits and sojourns abroad, and increasingly – from the 1910s and 1920s – international collaborations and exchange programmes, which led to communication between laboratory workers in various countries within Europe and to interactions between different laboratory cultures. As mentioned above, Liebig had travelled to Paris in the first third of the 19th century to witness the experimentation teaching of Joseph Louis Gay-Lussac (1778–1850), Louis Jacques Thénard (1777–1857) and other chemists. In the early 1840s, however, chemistry students from France and other countries attended experimentation lessons in Liebig's laboratory in Gießen. Among those students were Victor Regnault (1810–1878), Jules Pelouze (1807–1867) and Adolphe Wurtz (1817–1884).[29]

Wurtz subsequently became the director of his own laboratory for organic chemistry at the medical faculty in Paris. Having been promoted to Dean, he campaigned in the 1860s for the setting-up of appropriate teaching and research facilities for students of medicine. To this end, in the late 1860s he visited a number of laboratories at German-speaking universities which where considered as leaders in this respect. This journey was undertaken in an official capacity. The education minister Victor Duruy (1811–1894) had entrusted Wurtz on June 5th, 1868 with the task of "viewing and studying" scientific facilities at German-speaking universities, in particular those in Göttingen, Greifswald, Berlin, Leipzig, Prague, Vienna, Munich, Würzburg and Heidelberg. According to Duruy's instructions, Wurtz was to pay particular attention to laboratories, scientific collections, clinics and institutes for physiology

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28 With respect to the Bauhaus, see Moholy-Nagy, *Von Material zu Architektur*, 130. More generally, see Allesch, *Geschichte der psychologischen Ästhetik*, and Brain, *The Pulse of Modernism*.

29 Rocke, *Nationalizing Science*.

and pathology. The motive was not only scientific, but also explicitly political: “Please collect all the information about the scientific institutions in the neighbouring country which can be used for the benefit of our national education and teaching.”[30]

The corresponding *Rapport*, which Wurtz published in 1870, concentrated on descriptions of laboratories. The first part was dedicated to chemical laboratories; the second part dealt with laboratories of physiology; while the third and last part contained descriptions of the institutes for anatomy and pathological anatomy. Particular importance was given to drawings: on 17 tables, Wurtz reproduced detailed floor plans of the laboratories he had visited. Additional illustrations in the text gave views and cross-sections of the respective laboratory buildings. In Wurtz's opinion, combining these illustrations with the descriptive texts (that elucidated the principles governing laboratory operation as well as the financial situation of the teaching and research institutions Wurtz had visited) was the best way of fulfilling the task entrusted to him. According to Wurtz, the *Rapport* presented his impressions and memories in a balanced fashion: It avoided any uncalled for enthusiasm, which might have caused him to overstate the “glorious endeavours” of a foreign nation, as much as it avoided a weakness which would have caused him not to recognize these endeavours and to remain silent about them.[31]

As the eminent physiologist Claude Bernard (1813–1878) began his lectures on general physiology in Paris in the summer term of 1870, he made reference to Wurtz’s report. Bernard began with a brief overview of the history of his subject while emphasizing that not only “new discoveries and ideas” had been decisive in the development of physiology. According to Bernard, the “materials of work” and the “culture” of the discipline were also decisive factors.[32] What Bernard was referring to was the institutional context and technical equipment of physiological research. Given that three years earlier he himself had compiled an officially-commissioned report on the progress of general physiology in France, he was particularly familiar with these considerations.

Speaking only a few weeks before the outbreak of war with Prussia, Bernard contrasted in his lectures the poor state of physiology in France with the “splendid installations” available to physiologists in the neighbouring country. To demonstrate the contrast, he described the building and equipment of a top-class laboratory to his audience in the auditorium of the *Jardin des Plantes*. The laboratory in question was Carl Ludwig’s (1816–1895) physiological institute, which opened in 1869 in Leipzig and was the first institution of its kind to be fitted with a steam-engine as a central power source. But Bernard did not limit himself to a verbal description. He used visual aids to portray Ludwig's laboratory: “I place before you the floor plan of one of these [exemplary] laboratories, the one in Leipzig which is directed by Ludwig.

30 Wurtz, *Les Hautes Études Pratiques*, II.

31 Wurtz, *Les Hautes Études Pratiques*, III.

32 Bernard, *Leçons*.

[...] By this example, I want you to see the riches of these scientific installations, of which we in France have no idea."[33]

The floor plan mentioned is the one included in the *Rapport* by Wurtz (fig. 6). The horseshoe shape of the Leipzig laboratory building is immediately evident in the drawing. Contained within the horseshoe-shaped building were the workspaces for performing experiments in vivisection, biophysics and biochemistry, as well as rooms for spectroscopy, microscopy and work with mercury, in addition to a library. In the centre was the lecture theatre with space for an audience of around 150. The institute also contained living accommodation for the director and a mechanic, while the animals required for experimentation were kept in the garden. Rabbits, birds and frogs were kept in stalls, cages and aquariums which were erected opposite the opening of the horseshoe.

Bernard emphasized the differentiated completeness of Ludwig's laboratory. He found the division between different types of workspaces particularly important: "It is very important for efficient experimentation," he declared to his Paris audience, "to have separate rooms for experiments which require a particular instrument configuration. In this way, one avoids the loss of time which would result from setting up the instruments afresh and gathering the materials, which are sometimes very difficult to combine. This arrangement, which is basically only good use of time, could actually be extended to all scientific work."[34] The laboratory not only appears as an exemplary space of knowledge but also becomes the embodiment of a particular time regime which is also a regime of scientific work. 'Time is space' is the seemingly paradoxical thought put forth by Bernard regarding activity in the modern laboratory.

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33 Bernard, *Leçons*, 15.

34 Ibid.

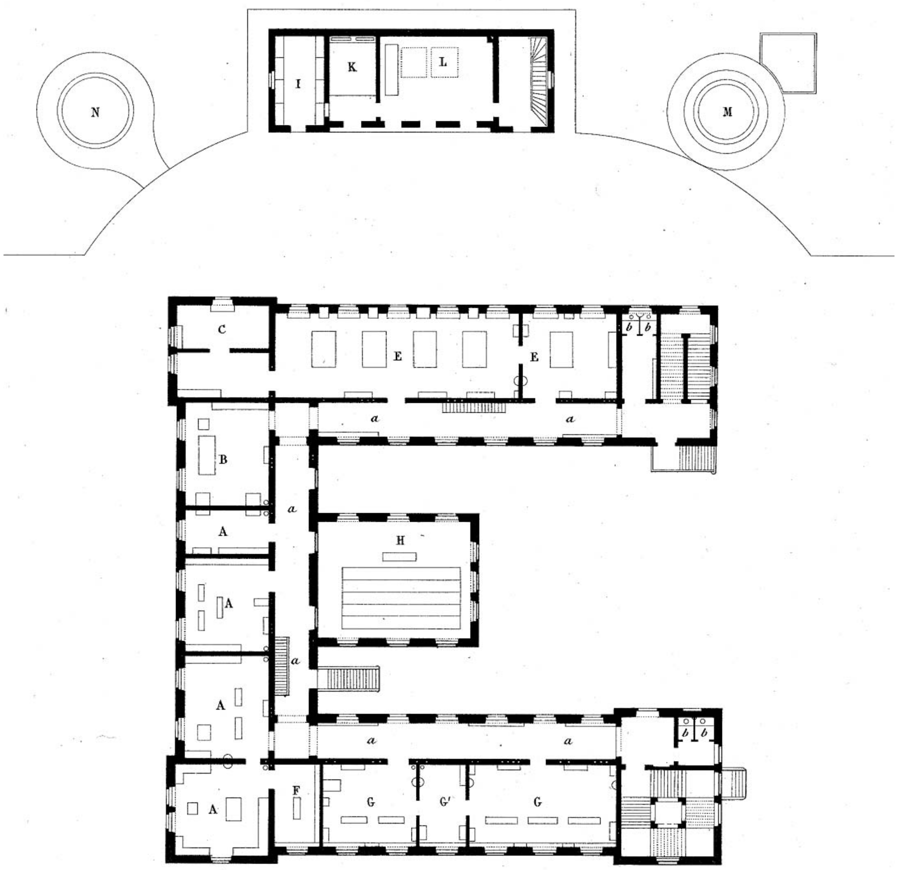

Figure 6: Plan of the ground floor in the Leipzig Laboratory for Physiology, 1870. Reproduced from: Adolphe Wurtz, *Les Hautes Études Pratiques dans les Universités Allemandes: Rapport présenté à Son Exc. M. le Ministre de l'Instruction publique*, Paris 1870, table XIV.

However, the Wurtz report of 1870 did not result in the direct transfer of the model to France. The considerable array of institutions in the German-speaking territories, which increased even further after the foundation of the *Kaiser-Wilhelm-Gesellschaft zur Förderung der Wissenschaften* in 1911, greatly outnumbered the corresponding institutions in France, which only included the laboratories of Wurtz at the *Ecole de médicine* and of Bernard at the *Collège de France* until Étienne-Jules Marey's (1830–1904) *Station physiologique* and the Pasteur Institute were added in the 1880s. Visits by German physiologists to laboratories in France were accordingly rare in this period.

One of the few examples of such visits was the "scientific journey" to Paris, Lyon und Bordeaux undertaken by the physiologist Maximilian von Frey (1852–1932), who worked in Leipzig at that time. In his short report, von Frey only mentions the laboratories of Marey and Pasteur in Paris and otherwise limits his descriptions to technical details of physiological instruments, such as the respiration apparatuses of Cheveau and Jolyet and the calorimeter of d'Arsonval.[35]

This further demonstrates the fact that the spread of the modern laboratory within Europe was not a uniform and one-dimensional process which can be adequately described using terms such as "rationalization," "mechanization" or "industrialization."[36] On the contrary, it was a multi-faceted process of transportation and transfer, of adaptations to local contexts and traditions, but which also contained individual examples of counter-transfers. Even in cases where an explicit attempt was made to follow the example of German-speaking institutions, translations occurred on the most varied of levels – the level of texts, of instruments and of experimentation procedures – and the information transferred was changed in the process.[37]

THE LABORATORY IN THE 20TH CENTURY

These transfers and translations continued to constitute an important factor in the spreading of laboratories during the 20th century. Evidence for this process is provided by the example of the Boston-based physiological chemist Francis G. Benedict (1870–1957). Between 1910 and 1930, Benedict repeatedly visited physiological laboratories all over Europe. Based on detailed reports and extended documentation, he intended to improve and enhance his own laboratory.[38] The fact that Benedict's reports contain numerous photographs attests to the increasing importance of this form of visualization in fixing and communicating laboratory knowledge.

During the first decades of the 20th century the modern laboratory became a global institution. In the realm of the experimental life sciences, this is illustrated, around 1930, by the Institute for Physiology at the University of Conception in Chile, the Science Laboratories of the Faculty of Arts and Science at Chulalankarana University in Bangkok or the Department of Physiology at Peking Union Medical College (fig. 7). While the exteriors of these laboratories were often adapted to their respective national contexts, their interior often consisted of things, e.g. instruments, imported from industrial countries and of persons, i.e. scholars, who either were from or had received their academic training in European or North American universities.

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35 Von Frey, "Kurzer Bericht."

36 Carroy and Schmidgen, "Reaktionsversuche in Leipzig, Paris und Würzburg."

37 The literature on the general history of German-French relations in the 19th century is obviously vast. On the area of science see Paul, *The Sorcerer's Apprentice*; Charle, *La république des universitaires*; and Bonah, *Instruire, guérir, servir*.

38 On Benedict, see Neswald, "Strategies of International Community-Building."

Figure 7: The Department of Physiology at Peking Union Medical College ca. 1925. Reproduced from: Ernest W. H. Cruickshank, „Peking Union Medical College, Department of Physiology", *Methods and Problems of Medical Education* 5 (1926): 65–75.

At the turn of the 20th century, a further result of these processes of transfer and translation can be seen. Besides scientific laboratories, a large number of "industrial laboratories" emerged. In the European context, this development was linked to the rapid growth of the dye industry, which in turn must be viewed in the context of the history of modern chemistry. Heinrich Caro (1834–1910), who in 1868 assumed a leading position at the recently founded *Badische Anilin- und Sodafabrik* (BASF), and Eugen Lucius (1834–1903), a co-founder of the company which was subsequently known as Hoechst, had both trained as chemists. Lucius had even been a student of Bunsen. In the 1870s and 1880s, companies such as *Hoechst*, *Agfa* and *Bayer* began to employ chemists in large numbers, in some cases in laboratories specially built by the companies.

Similar developments occurred in the USA at the same time, albeit in other branches of industry. In 1875, the *Pennsylvania Railroad Company* set up its own research laboratory, followed by *Eastman Kodak* in 1886 and *General Electric* in 1900, the latter after one of its founding directors, Thomas Alva Edison (1847–1931), had run similar laboratories in Menlo Park (1876) and West Orange (1886).

As in Europe, the goal of these laboratories was to produce useful knowledge which could be employed for commercial advantage. Instead of publishing articles in scientific journals, the researchers in these laboratories were interested in getting patents recognized so as to have commercial control of the processes and products involved in their research. To a degree, they resembled the alchemists in their laboratories: They produced results in a very deliberate fashion, and the means by which these results were obtained was only shared with other “initiates.”[39]

Another result of the processes of transfer and translation which the laboratory experienced at the turn of the 20th century was the emergence of large-scale laboratories, usually in military complexes. Typical of this development was the restructuring of the Kaiser Wilhelm Institute for Physical Chemistry and Electrochemistry in Berlin by Fritz Haber (1868–1934) during the First World War. At the end of 1918, this institute had 1,450 employees. Most of them were engaged in the development of gas weapons and the means of protecting against gas weapons.

The research institutions which emerged during the Second World War were even larger. One of the most famous was the Los Alamos National Laboratory founded by the USA in 1943, in which the atomic weapons programme of the United States was initiated as part of the Manhattan Project (See the related article “Manhattan Project”). Employing at one time more than 120,000 people, this project marked the irreversible entry into the era of “Big Science,” in which the growth of science is no longer exclusively measured by the number of publications or patents, growth in scientific personnel and the level of state funding devoted to research, but also by the exponential increase in the energy usage of particle accelerators.[40]

The second half of the 20th century saw the intensification of the founding of industrial laboratories and the emergence of large-scale laboratories, which increased the worldwide competition affecting private and public laboratories of all types and sizes. (See the related article “Materials Science”) Against this background one can observe the emergence of a new type of large laboratories. This new type was meant to foster rationalized, quasi-industrial forms of research while also providing latitude for innovative forms of interdisciplinary cooperation. The corresponding buildings were no longer molded on single disciplines. They constituted centers and envisioned overarching “programs” or “areas of research” with shifting horizons of time. On the level of architecture, these new laboratories featured large structures with variable layouts that could be adapted to the specific needs and interests of dynamic research groups. At the same time, they provided meeting places such as “streets” or “plazas” that serve as *trading zones* for international scientists from different disciplines or mixed groups of scientists, engineers, and computer experts.[41]

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39 Bowker, “Manufacturing Truth,” 588.

40 Price, *Little Science, Big Science*. On large-scale research in Europe, see, for example, Trischler, “Wolfgang Gentner.”

41 For “trading zones” in laboratories, see Galison, *Image and Logic*, 803–844.

Within the life sciences, the spectecular example for this new kind of laboratory is the Salk Instiute for Biological Research built by reknowned architect Louis I. Kahn (1901–1974) in 1965 for the leading physician and immunologist Jonas Salk (1914–1995). In the early 1960s, Kahn had risen to prominence with his futuristic new main building for the Yale University Art Gallery, but above all with his plans for the Richards Medical Research Laboratories building at the University of Pennsylvania. This design featured three towers containing laboratories connected with a central service tower; the laboratories used by people, the "served spaces," were separated from the "servant spaces," which contained mechanical systems, lifts, animal quarters, etc. Designed originally for each floor to be one large room, partitions could be employed to accommodate the changing needs of the scientists. Salk had similarly open structures in mind for the biological research center he was planning.[42]

The basic structure of the laboratory building, situated near San Diego directly on the cliffs of the Pacific Ocean, is characterized by two symmetrical building structures facing each other lengthways; they are separated from and connected to each other by a grand courtyard that gives onto the ocean like the stage of an open air theater—an impression reinforced by a stream of water that flows down the middle of the courtyard in the direction of the ocean (fig. 8). The deep embedding of the building complex into the landscape is further emphasized by the fact that from the courtyard the laboratories are hardly visible. The actual rooms where research is done are beneath the courtyard and in the rear sections of the two symmetrical buildings. At the front are the scientists' studies, which look out onto both the courtyard and the ocean.

Kahn's client referred to these studies as "monk's cells," which points to scientists' need for concentrated study and also indicates that Salk saw his institute in some measure as a spiritual place. In fact, with the clean lines of its design and its durable, basic, and low-maintenance materials (concrete, wood, glass, and steel) it is not difficult to see this institute as a modern monastery—or as a high-tech version of the Grand Canyon, where the simultaneity of silent depths and openness has a similarly awe-inspiring effect on the beholder.

42 On Kahn and Salk, see Legault, "Louis Kahn und das Eigenleben des Materials."

Figure 8: The courtyard of the Salk Institute for Biological Studies in La Jolla, San Diego. Reproduced from: *Wikipedia,* By Codera23 - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=81787561.

Completed in 1965, the buildings were soon in use. It did not take Salk very long to attract a group of eminent medical scientists and biologists to his institute: Jacob Bronowski (1908–1974), Leslie Orgel (1927–2007), and the later Nobel laureates Robert Holley (1922–1993) and Roger Guillemin (1924–), as well as luminaries like Francis Crick (1916–2004), Jacques Monod (1910–1976), and Warren Weaver (1894–1978) as nonresident fellows. Besides immunology, endocrinology, and neurology, molecular and cellular biology constituted crucial areas of research.

The Salk Institute also functioned as a site for international exchange between the life sciences and the humanities. Linguists such as Roman Jakobson (1896–1982) as well as writers such as Michael Crichton (1942–2008) were fellows of the Institute in the late 1960s. From France, sociologists such as Edgar Morin (1921–) were invited as research guests as well as philosopher and anthropologist Bruno Latour (1947–). From Winter 1975 to summer 1977, Latour would gather in one of the laboratories at the Salk Institute the raw data for what, in later years, would be considered as a path-breaking contribution to the emerging field of “laboratory studies.”

Laboratory Life, which Latour wrote and published together with Steve Woolgar, a British sociologist of science, attracted the interest of historians of science immediately after its publication in 1979. Today it is recognized as a “modern classic” and, because of its programmatic significance, sometimes compared with Thomas Kuhn's *The Structure of Scientific Revolutions.*[43] At the center of the book, however, is not the laboratory of Gullimemin that Latour had studied but the process of "tradition," in which a group of scientists -- via discourse and words, writing and paper, hands and inscription devices -- act in such a way that, according to Latour, can scarcely be comprehended by a modern, secularized notion of history.

In the anthropologically oriented chapters of *Laboratory Life* mention is made of the rotary evaporators, centrifuges, mixers, and other "machines" by the aid of which the laboratory staff of the Guillemin laboratory cut, grind, shake, and so forth the organic material they work with.[44] However, the main theme of these anthropological parts is the writing desks upon which very different types of literature—published journal articles, computer printouts with columns of figures, diagrams, tables, manuscripts, and so on—are collected before being transformed into scientific publications. In other words, Latour and Woolgar make sure that from an anthropological point of view scientific work in the laboratory should be understood as "literary inscription."[45]

Though it stimulated a great deal of scholarship on the institution of the laboratory, *Laboratory Life* makes it somewhat difficult to situate the laboratory in the history of modernity. According to Latour, "we have never been modern,"[46] and correspondingly the laboratory appears in his studies as an exegetical institution, an institution primarily concerned with the generation and interpretation of written signs. In other words, the aspect of production is largely neglected, whereas the aspect of representation moves to center stage. In Latour, the laboratory tends to become again a *scriptorium*.

Viewed from today's perspective, this notion of the laboratory could have been based in a broader notion of the modern emphasis on technologies, machines and infrastructures which make possible and shape the process of writing and the production of laboratory inscriptions. In Latour's acount, however, the computer and similar information technologies hardly play a role. Even if, in later years, he describes the laboratory as a "center of calculation," he remains committed to considering to the world of scientific practice predominantly as a "paper world."[47]

Nearly a half-century later, however, it is the extension of laboratory architectures into the virtual space of databases, models, and simulations that confirms the dominant model of

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43 Rip, "Citation for Bruno Latour," 379.

44 Latour and Woolgar, *Laboratory Life*, 67.

45 Ibid., 47.

46 Bruno Latour, *We Have Never Been Modern*.

47 Shapin, "Following Scientists Around."

the laboratory while also contributing to its dispersion into new forms. Particularly striking in this respect is the fact that the dominant information and communication technology of today, the World Wide Web (WWW), emerged from the work conducted in the rather vast laboratory of CERN. The main purpose of this work was to facilitate the international exchange between laboratory scientists and give them better access to the existing knowledge of their respective fields. In the late 1980s, the CERN physicist and computer scientist Tim Berners-Lee (1955–) developed "Hypertext Markup Language" (HTML) which remains the basis for the public use of the Internet.[48]

At this point the iconography of the laboratory as an isolated, self-contained structure in which equally isolated scientists sit in front of a microscope, point to a curve on a chart or stand next to a DNA model is factually outdated – even though it might continue to play an important role in popularizing science. Today's "laboratory" is a globally networked knowledge infrastructure tied together by digital technologies. Using "Big Data" and developing "Artificial Intelligence" (AI), this infrastructure allows for performing innovative experiments in real and virtual space, for example distributed experiments in ecology.[49] Within this network, single laboratories continue to constitute crucial nodes where combinations and confrontations of human and machine, body and technology, organisms and instruments continue to occur in order to produce similarly innovative results.

CONCLUSION

Laboratories are exemplary sites of modernity. However, they do not only function as passive reflections of an increasingly gobalized and digitalized society, but also as active examples, as forces for change whose influence is by no means limited to the natural sciences and the humanities. Besides new knowledge and technologies, laboratories produce new types of people. They train scientists and researchers, who learn to strive as both individuals and as part of a collective, and who enter into a performance-related competition supposedly governed by transparent rules and fair behavior but simultaneously marked by fierce competition with respect to material as well as immaterial resources.

In this and other regards, historical analogies bewteen the laboratory and the factory fail to provide an adequate picture. As a site of education and practice, comparisons between the laboratory and, for example, the gymnastics hall or the sports field are just as valid. In fact, this parallel is drawn explicitly in many universities in order to demonstrate the principle of the unity of research and teaching.

It is not just the university that becomes "a laboratory where everyone is busy, and where enthusiasm in study is the predominant characteristic," as Daniel Coit Gilman (1831–1908),

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48 Berners-Lee and Fischetti, *Weaving the Web*.

49 See, for example, Borer, Harpole, Adler, Lind, Orrock, Seabloom and Smith, "Finding Generality in Ecology," and Michener, "Ecological Data Sharing," as well as, more generally, Coleman, *Big Ecology*.

the founder of the Johns Hopkins University, put it in 1883. In the programmatic view of Gilman, the entire world is "a great laboratory, in which human society is busy experimenting."[50] This view of an 'experimentation society,' or of modernity itself as subjected to the mode of experiment, is another aspect of the development of the laboratory. This process has fundamentally transformed – and will continue to transform – the meaning of science and society.

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50 Owens, "Pure and Sound Government," 184.

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