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Organizing a Scientific System: the Emerging Networks of Modern Chemistry (1680-1860)

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Abstract

This article analyses the networks that structured chemistry as a discipline in the 18th and 19th centuries. It first examines the participation of chemists to the 18th century system of epistolary exchanges (the Republic of letters). It then focuses on the collaborations, which gave an increasing momentum to the community of chemists, and on the training links, which conditioned the entrance into an emerging scientific field. The analysis is based on a sample of 1420 specialists representative of the Western chemists active between 1680 and 1860. This sample shows that two thirds of these chemists came from France, Great Britain and Germany. The French community was the first to take a national character by the middle of the 18th century, but chemistry also became a national reality in Germany at the turn of the 19th century. Within these national contexts, training and collaborations increased in specialization and density, especially after the beginnings of the "Chemical Revolution" in the 1770s and even more so after the reform of the German universities in the 1830s. There, a few professors combining laboratory training to theory taught chemistry on an "industrial" scale and attracted scholars from Russia, the United States and Great Britain. International collaborations, started at an individual level in German and French laboratories, also contributed to implement modern chemistry into an increasing number of countries. The modern field of chemistry was symbolically established in 1860 with the first international congress of nomenclature held in Karlsruhe.
Keywords: *networks, chemistry, scientific training, scientific collaboration, specialization, professionalization*

Résumé

Elaborer un système scientifique: les premiers réseaux de la chimie moderne (1680-1860). – *Cet article porte sur les réseaux qui ont matérialisé la constitution de la chimie en discipline autonome au cours des 18e et 19e siècles. Il s'efforce notamment de décrire les liens de formation, qui conditionnent l'entrée dans un champ scientifique émergent, ainsi que les collaborations qui lui donnent de la substance. La participation des chimistes aux échanges épistolaires de la République des lettres est aussi examinée. L'analyse repose sur un échantillon de 1420 spécialistes représentatifs de l'ensemble de la communauté des chimistes occidentaux entre 1680 et 1860. Elle démontre que deux tiers de ces chimistes proviennent de France, de Grande-Bretagne et d'Allemagne. La communauté française fut la première à prendre un caractère national, vers le milieu du 18e siècle, mais la chimie allemande devient également une réalité nationale au tournant du 19e siècle. Dans ces contextes nationaux, les formations deviennent de plus en plus spécialisées et les collaborations de plus en plus denses, notamment après les débuts de la « Révolution chimique » des années 1770, et plus encore après la réforme des universités allemandes des années 1830. Quelques professeurs, combinant apprentissage en laboratoire et théorie, y forment des chimistes à une échelle industrielle, dont certains proviennent de Russie, des Etats-Unis et de Grande-Bretagne. Un nombre croissant de collaborations internationales débutent aussi dans ces laboratoires allemands, ou français, contribuant du même coup à l'implantation de la chimie moderne dans de nouveaux pays. Le système scientifique de la chimie moderne prend symboliquement naissance en 1860 avec le premier congrès international de nomenclature, organisé à Karlsruhe.*
Mots-clés: *réseaux, chimie, formation scientifique, collaboration scientifique, spécialisation, professionnalisation*

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Perspectives and method

According to Latour, the capacity of individuals, groups or nations to participate in the developments of modern science is directly dependent on their ability to be connected to the networks of the international science system, at the local as well as at the global level[1]. These connections allow scientists or groups of scientists to integrate the main system of scientific communication. This system is not limited to members of academies and scientific societies, or to authors of scientific articles and textbooks, even though it can only function if the empirical results and proposed theories are validated by scholars considered competent by the international scientific community. It is open to persons who have an access to teaching and research infrastructures, such as laboratories, observatories, botanic gardens, museums or clinics and more generally universities and technical schools[2]. This integration process allows for the expansion of the international scientific system to new individuals and communities[3].

Despite its promising perspectives, few historians of the Early Modern period have taken Latour's model as the basis of their empirical investigations[4]. Most of those who paid attention to scientific networks model, have focused their analysis on the ideals motivating scholarly collaboration[5] or have limited their empirical investigations to the epistolary network of a single scholar[6]. It is true that many historians have tried to set up more ambitious analysis, but their respect for the complexity of the matter has usually restricted the scope of their conclusions[7]. My own focus on science, and especially on chemistry, is obviously a way to simplify the matter. Defining chemists in a formal way, and limiting the analysis to training, patronage and to collaborative links, is a further simplification. Using Latour's model as guideline for an empirical investigation aimed at characterizing the emergence of a discipline (or a sub-system of Early Modern science), is possibly a third kind of simplification. This paradigm shall nevertheless define the broad outlines of this article, whose aims are: 1° to identify a few "dominant centres" that structured and organized the nascent discipline of chemistry; 2° to identify the more dynamic clusters of specialists existing at different periods; and 3° to localize some of the ever changing channels of knowledge transfers.

In this article, the focus will be set both on training (and patronage) links and on collaborative links that shaped the new disciplinary community and its various local and national subsets. Behind these connections, one may perceive the social and institutional factors that fostered the development of chemistry. Yet, the detailed study of these factors is not part of the present enquiry. A short methodological conclusion will explore how this evolving geography of chemical networks can possibly contribute to a better understanding of the historical dynamics of Early Modern science.

The information on these networks is provided by a systematic compilation of biographical data about some 1420 chemists active between 1680 and 1890 (and for a few of them earlier in the 17th century). This data, stored in an extensive database, is taken from a great variety of printed sources[8]. As it involves all outstanding scholars specialized in chemical research, I hope that this sample of study can be considered representative of the whole community of chemists of the Western world.

16th and 17th century chemists: on the margins of the Republic of Letters

In European history, the first significant movement of scholarly collaboration was associated with the notion of "Republic of Letters" (*Respublica literaria*) that first took shape in late 15th century Italy and spread to Western and Northern Europe in early 16th century. This ideal was defined by some humanists who wanted to encourage philologists and scholars of all political allegiances to participate in a collective enterprise of "Restoration of knowledge". The aim of this undertaking was to reconstruct in their pristine purity the works of classical authors and scholars. Mathematical and scientific texts were part of this philological

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1 Latour (1987). It is from the study of scientific practice that Latour derives his analysis of science as a process of network building. He notably sees the practice of references and citations, and the production of pictures, as ways to mobilize connections and resources against possible attacks.

2 Because science has to be funded, it must enlist many social actors to happen, and therefore needs to expand its web of connections beyond the scientific world properly speaking.

3 Expanding science into a global enterprise does not exclude the existence of centres and peripheries.

4 Latour's *Science in Action* has been criticized, sometimes heavily, by many historians.

5 Daston 1991a, Goldgar (1995), Bots & Waquet (1997), Bury (1999).

6 Stuber & al. (2005) is a perfect example of analysis of such an ego-network.

7 Among the themes related to the history of scholarly networks in the Early Modern period are the genesis of the Republic of letters (Schalk 1977), the role of epistolary practice in the exchanges of natural specimens (Secord 1994), the features of patronage and trade in services (Stegeman 1996), the interface between institutions and networks (Zijderveld 2000) or the emergence of properly scientific networks (Vittu 2002).

8 Among others, the *Dictionary of Scientific Biography* (Gillipsie (dir.) 1970-1980), various dictionaries of national biographies (*Oxford Dictionary of National Biography*, *Dictionnaire de Biographie Française*, *Neue Deutsche Biographie*, *Svenskt Biografiskt Lexikon*, *Dizionario Biografico degli Italiani* and so forth), as well as the online compendium of biographical dictionaries labeled *World Biographical Information System*.

enterprise, with the advantage that observation and logical reasoning, which were of no use for the restitution of literary or sacred texts, could sometimes help the reconstruction of anatomical, botanical or mathematical treatises. Alchemy was only marginally involved in this process, even though a few practical texts translated from the Arabic helped identifying and producing the fundamental tools of a well-equipped (al)chemical laboratory. In the 17th century, references to modern scholars, including the very controversial Paracelsus, quickly replaced most traditional authorities with the exception of Euclides[9].

The decline of philological humanism did not put an end to the Republic of Letters, which took a new shape and connected new kinds of scholars in the 17th century. Already in the late 16th century, small groups of physicians, astronomers and naturalists had started to exchange empirical data in letters[10]. Collectors of curiosities, historians, antiquarians and universal scholars (*polyhistor*) also exchanged vast amounts of empirical data and anecdotes. Some scientific information was therefore conveyed through these epistolary networks. Important nodes of scholarly communication coalesced around the "academies" of Mersenne, Bourdelot and Montmor in Paris or the Gresham and Wadham "colleges" in London. The creation of the first permanent academies (Royal Society in London, *Académie des Sciences* in Paris, *Academia Naturae Curiosorum* in Germany) significantly reinforced the participation of "scientists" in the networks of the Republic of Letters. At the end of the 17th century, these ideals of scholarly collaboration would acquire an increased consistency with the publication of scholarly periodicals edited by independent journalists (*Journal des Savants*, *Acta Eruditorum*) or by academies (*Philosophical Transactions*, *Mémoires de l'Académie des Sciences*). They coexisted with universal periodicals such as Pierre Bayle's *Nouvelles de la République des Lettres*, Jean Le Clerc's *Bibliothèque choisie* and many others published by Huguenot refugees[11]. In all these scholarly exchanges, the chemists played a marginal role, be they Paracelsian or Helmontian physicians, mining engineers, craftsmen or expert manufacturers.

During the 18th century, the Republic of Letters, which usually included "Sciences and Arts" (in the sense of technical knowledge), still provided an ideal reference for scholarly collaboration. It promoted a model of conduct able to mobilize the good will of scholars working in various local contexts. Academic affiliations and positive reviews in periodicals were the only rewards they could expect for their contributions to science and scholarship in general. But these rewards were conditioned to the respect of an unwritten gentlemanly code of conduct requiring assistance to fellow scholars and the avoidance of personal attacks in controversies[12]. Chemists acquired an intellectual and social visibility by 1666 when some of them became members of the new *Académie des Sciences* established in Paris, and even more when chemistry became one of the six sections created in 1699 within the *Académie*. Yet, of the 80 correspondents elected this year, only two (2,5%) were registered as chemists. It is very few compared to 18 astronomers (22,5%) or 14 botanists (17,5%), even though some of the 20 physicians (25%) were indeed practicing medical chemistry as well.

The increasing dominance of science in the academies and in the epistolary exchanges between scholars created some tensions within the universal Republic of Letters[13]. Yet, the notion of Republic of Science as a separate entity would never be totally accepted[14]. The French "philosophes", who wanted to maintain a global and non-specialized culture associating letters and science, fought for instance against the use of specialized terminologies[15]. Their attempt to give an ideological content and a political significance to the culture of Enlightenment went also against the original spirit of the Republic of Letters, which enforced political abstinence and theoretical neutrality. Therefore, a growing division appeared between the Royal academies on the one hand and the mundane salons on the other. Various subsets of specialists also emerged within the academic world, especially mathematicians, astronomers and botanists. Scholars such as Linnaeus and Johann III Bernoulli even coined the expressions of "Republic of botanists" (*Respublica botanici*) and "Astronomical Republic" to name two of these emerging disciplinary networks[16].

Eighteenth century men of science sometimes exchanged letters with hundreds of colleagues and had significant exchanges with dozens of them. The threshold defining a significant exchange regardless of the content is of course difficult to determine, and it is obvious that scientific, literary and personal contents are inextricably mixed in most letters. To allow for comparison, a scale of intensity has nevertheless to be established. Its first degree – the threshold of significance – would be materialized by a stream of 10 letters addressed by one scholar to another. Further degrees of intensity would be determined by thresholds of 20, 50, 100, 200, 300, 500 and 1000 letters written

9 On the emergence of a modern scientific field around the 1630s, seen through the authors quoted in Mersenne's correspondence, see Gingras (2010).

10 Pomata (2011).

11 On these periodicals, edited by scholars such as Michel de la Roche, Pierre Desmaizeaux, Jean Henri Samuel Formey or Louis Bourguet, see Sgard (1991).

12 Goldgar (1995).

13 Schandler (2008).

14 Sigrist (2008a).

15 For their fight against the establishment of political economy as an autonomous science, see Abrosimov (2008).

16 Sigrist (2008a).

Table 1: Thematic orientation of the correspondence exchanges of 51 major scientists of the 18th century grouped according to their main field of enquiry.

	Number of links	Number of scientists	Average number of links	Same field (largely defined)	Same field (strictly defined)
Mathematicians (pure & applied)	269	12	22,4	48 %	38 %
Astronomers	394	5	78,8	50 %	38 %
Physicists (math. & theor.)	110	5	22.0	50 %	19 %
Life scientists	583	11	53,0	67 %	---
Chemists & exper. physicists	146	7	20,8	38 %	28 %
« Philosophes »	183	5	36,6	22 %	---
Earth scientists	81	6	13,5	14 %	---
TOTAL	**1766**	**51**	**34,5**		

on either side. The accumulation of these links, qualified by their intensity, can be used to define the degree of centrality or the "importance" of an ego-network, and therefore of a given scientist[17]. On that basis, it is possible to define the proportion of links established between scientists working in the same field, and therefore to have an idea of the approximate degrees of specialization of various disciplines.

According to these criteria, applied to 51 scientists of the 18th century, it appears that the most specialized subset of scholars was the botanist, who exchanged nearly half of their letters with other botanists and nearly three quarters with other life scientists, especially naturalists (Table 1). Other distinctive clusters of epistolary exchanges group mathematicians, who had a professional identity since the middle of the 16th century, and astronomers, who enjoyed strong public support in many countries and towns. Chemists and physicists, especially "particular" physicists (who rely on experimentation more than on mathematics or theory), appear as a more diffuse entity, characterized by a high proportion of epistolary exchanges with other groups of scholars. Yet, their degree of specialization is still higher than that of geologists, meteorologists or physicians, and of the universally minded "philosophes". The average size of the networks of chemists and experimental physicists (measured again in terms of significant exchanges) is also much smaller than those of astronomers, botanists and physicians, who collected and exchanged enormous amounts of empirical data. Curiously enough, their experimental practice did not require in average more epistolary exchanges than the practice of pure and applied mathematics or "general" physics.

Despite their growing number, chemists and experimental physicists apparently had a rather weak sense of belonging to a structured community of specialists, even though this sense was still weaker among Earth scientists. In other words, the emergence of specialized networks of chemists was a rather marginal phenomenon within the 18th century Republic of Letters and Science.

Debates about the origins of modern chemistry

Traditionally, the birth of modern chemistry was assigned to a "Chemical Revolution" or a "Pneumatic Revolution" which took place in the 1770s and 1780s[18]. The first theoretical paradigm of the new discipline was provided by the theory of oxygen as an explanation of combustion, calcining and acidification. The isolation of elements and the systematic use of the balance were also supposed to provide the first methodological paradigm of chemistry, while the use of a new nomenclature was considered to have sealed the whole process of paradigmatic change. The Kuhnian requirement for the establishment of a new science based on a shared paradigm was thus fulfilled by the chemistry of Lavoisier and consorts. This paradigmadic dimension was usually denied to the earlier phlogiston theory shaped by Becher and Stahl.

As many certainties in the history of science, this one has been gradually deconstructed. Already in the 1980s, Frederic L. Holmes had shown the existence in 18th century chemistry, and especially within the chemistry of salts, of features suggesting an earlier paradigm[19]. Since then, new arguments have been added in favour of an earlier birth of modern chemistry. In a synthetic article, Lawrence M. Principe wrote, for instance, that changes that happened in chemistry between 1675 and 1725 had the weight of a true scientific revolution, even though very few people noticed it[20]. These changes first affected the aims and applications of chemistry, with the abandon of metallic transmutations as a legitimate target and the

[17] Sigrist (2008b).

[18] The question of the origins of Early Modern chemistry, or « chymistry » (to designate a mixture of alchemical and chemical features) is another one. It can probably be assigned to the 16th century, with the birth of Paracelsism and iatrochemistry, the development of a "chemical philosophy" and the publication of textbooks on mining engineering.

[19] Holmes (1989).

[20] Principe (2007, p. 7).

development of new chemical practices. The second feature was the increase in status and professionalization of chemists, with the creation of the first chairs of chemistry and also with the first academic pensions awarded to chemists. Last but not least, the period saw a remarkable fertility of theoretical innovations based on experimental and practical results. For their part, Ursula Klein and Wolfgang Lefèvre stated that even though Lavoisier and his collaborators introduced reforms in the concepts, theories, analytical methods and language of chemistry, they did neither initiate an ontological rupture nor overthrow the existing taxonomic structure of chemical substances[21]. According to them, major changes occurred around 1700, when chemists decided to break away from a natural philosophy looking for the first principles of matter or for spiritualized essences. They started instead to test chemical properties such as combustibility, acidity, solubility in various solvents, as well as their interactions with different reagents. Dissociating chemical compounds into different substance components held together by chemical affinities, and using the obtained ingredients to re-synthesize the original compound, had then become the basic tasks of analytical chemistry. The notion of reversible chemical transformation, the concept of chemical affinity and Stahl's theory of phlogiston were thus the first components of a true chemical paradigm, which shifted attention from the imperceptible properties of matter to the perceptible dimension of chemical substances. The first chemical classifications based on this paradigm were expressed by affinity tables such as the one set up in 1718 by Etienne-François Geoffroy[22].

The existence of a fundamental transformation in the way chemistry was conceived and perceived also appeared through the creation, in the late 17th century, of the first institutions devoted to chemistry. A few German universities introduced the teaching of chemistry within different curricula: pharmacy (Marburg, 1609), practical medicine (Jena, 1673) or even anatomy (Altdorf, 1677). In France, where the use of chemical remedies had long been contested by the medical faculty of Paris during a hundred years debate over the uses of antimony (1566-1666), a first course in chemistry was established in 1635 at the "Jardin du roi" and a second chair added before the end of the century. The medical faculty of Montpellier established its own chair of chemistry in 1697. A further teaching of chemistry was introduced in 1702 at the Pharmacy garden in Paris, equipped two years earlier with a fine laboratory. Even more significant was the inclusion, after 1666, of a few chemists among the "pensionnaires" of the newly established "Académie royale des Sciences". In 1678, a chemical laboratory was set up in Louvre and in 1699 a whole section of chemistry appeared within the reformed "Académie des Sciences".

In Sweden, a *Bergskollegium* was founded in Stockholm in 1678 in order to improve the management of mines. In 1684, it was equipped with a laboratory to teach the science of mines and metallurgy, which became the training sector of many chemists. On this model, a few German states (Brunswick, Saxony, Prussia) would later create their own council of mines to manage their mining resources in a more rational way. In England, the first chemistry teachers, for pharmacists, appeared just after the Restoration of 1660. The London *Apothecaries' Hall* became in 1672 the first large scale producer of chemical products. In Cambridge, John Francis Vigani, who had taught pharmaceutical chemistry since the early 1680s, was named honorary professor in 1703. Yet, the first chair of chemistry of a European significance was established in 1718 by the University of Leyden. Hermann Boerhaave, its first incumbent, already enjoyed a large reputation as a professor of medicine and botany. From now on, his numerous students would diffuse medical chemistry throughout Europe. All these institutions provided a new generation of chemists with training and research opportunities that did not exist before. An international network of chemists would gradually emerge, defining chemistry as a scientific practice at the crossroads of natural philosophy, natural history, technology and of course medical sciences (including pharmacy). The development of such a network of specialists coincided with the establishment of a more formal training, which increased the level of competence expected from specialists. The scientific misfortunes of amateurs such as Voltaire in physics and in the Earth sciences and Jean-Jacques Rousseau in chemistry may illustrate the increasing requirements of chemistry and at 18th century science in general.

Entering the chemical networks: the importance of training, patronage and specialization

In the wake of the success of his *Letters Concerning the English Nation* (1734), Voltaire had taken a keen interest in Newton. Powerfully helped by the mathematical abilities of his close friend Emilie du Châtelet, he successively published an *Epître sur Newton* (1736) and some *Eléments de la philosophie* de Newton (1738). At this point, his aim might have been to succeed to the ageing Fontenelle as perpetual secretary of the "Académie des Sciences"[23]. But if the road to literary fame was an arduous one,

[21] Klein & Lefevre (2007, p. 2).

[22] Klein & Lefevre (2007).

[23] According to Carozzi (1983, p. 14 et 49), this was Voltaire's ultimate ambition at this time.

becoming a recognized man of science required overcoming a lot of practical difficulties. Understanding Newton's *Principia* proved a very difficult task, even with the benevolent help of Emilie du Châtelet. After her death (1749), Voltaire limited his scientific ambitions to a few incursions in the field of the Earth sciences, possibly the less formally established at that time and therefore the most accessible of all[24]. Yet, his attempt to participate in the debates about the origins of fossils proved vain. What he earned was little more than the fierce critiques – and even the sarcasms – of Buffon and of the geologist Guettard[25].

In 1743, another science – chemistry – suddenly became fashionable in France, when Guillaume-François Rouelle (1703-1770) opened his first cycle of demonstrations at the "Jardin du roi" [26]. Among his numerous auditors was a man of letters and would be "philosophe" of 31 years of age: Jean-Jacques Rousseau. One year before, he had already tried to call on himself the attention of the "Académie des Sciences" by submitting a new system of musical notation. In vain. After another year spent in Venice as a secretary to the French ambassador, Rousseau returned to Paris and attended Rouelle's lectures for a second time (1745). In the meantime, he had become private tutor of Louis Dupin de Francueil (1715-1786), a wealthy young man who apparently ambitioned to become affiliated to the "Académie des Sciences". Rousseau himself soon felt confident enough in his knowledge of chemistry to give private lessons to a gentleman called Claude Varenne de Beost, who would later take an interest in the introduction of potato in France. His employer Dupin soon asked him to establish a chemical laboratory in his property of Chenonceaux, the famous Renaissance palace on the river Cher. While making a few experiments there, Rousseau was also requested to compile the best available textbooks on chemistry in order to produce a new compendium entitled *Institutions chymiques*. His choice fell on Johann Joachim Becher's *Institutiones Chymicae* de (1664), Jean-Baptiste Senac's *Nouveau cours de chimie d'après les principes de Newton et de Stahl* (1723), Johann Juncker's *Conspectus Chemiae theoretico-practicae* de (1730), and Hermann Boerhaave's *Elementa Chemiae* (1732), completed by a few academic memoirs. A three volumes manuscript of 1206 pages divided into four sections was written down by 1747, when the project was suddenly abandoned[27]. At this time, Dupin might have realized that a successful career in the field of chemistry would be much harder than he expected. It required not only means and ambition, but also talent and perseverance, as well as the help of some well-disposed and well-connected patrons. Rousseau himself would soon explore another way towards literary fame, a goal he started to achieve in 1750 with the Academy of Dijon prize for his controversial *Discours sur les sciences et les arts*. Curiously enough, it was by criticizing most of the scientific and literary enterprise on moral grounds that he made it into the world of letters.

With the exception of d'Alembert and Condorcet, who were true mathematicians turned "philosophes", and to a certain point d'Holbach, who specialized in translations of German chemists and naturalists, "philosophes" and men of science were already following diverging paths. The former still enjoyed more consideration from the public and from enlightened monarchs[28]. It is true that the literary approach of scientific matters practiced by the "philosophes" made them much more accessible to a lay audience than the technical language of scientific discourses. The case of Denis Diderot may illustrate this point. Like his friend Rousseau, Diderot attended Rouelle's demonstrations at the "Jardin du Roi". But contrary to his Genevan colleague, he would persist in his "philosophical" interest for chemistry, which was very different from an empirical practice of chemistry. Diderot was not much interested in the technical developments of chemistry, leaving the task of writing the articles of the *Encyclopédie* related to chemistry to Gabriel François Venel, a recognized chemist and true disciple of Rouelle. As a man of letters and "philosophe", Diderot enjoyed speculations about the possible causes of chemical affinities and about their role in the physiology of life. He also reflected on the origins of elements, or the role of fermentation in the genesis of life. Those were reflections of a free mind who did not hesitate to speculate about the possible significance of concepts associated with chemistry[29]. Yet his conclusions were not considered significant contributions to the positive science of materials.

Diderot's position is emblematic of the ambiguities of Enlightenment science. His theoretical views could potentially be discussed in the literary salons and throughout the Republic of letters. But despite his publication, with Venel, of a few articles on chemistry in the *Encyclopédie*, he was hardly better integrated to the emerging networks of academic chemistry than Rousseau or Dupin. On the eve of the "Chemi-

23 On Voltaire's geology, see Carozzi (1983).

25 On Voltaire's attempt to have his views on fossils confirmed by the Swiss naturalist Elie Bertrand, see Sigrist (forthcoming 2).

26 On the teaching of chemistry in mid-18th century France, see Bensaude-Vincent & Lehman (2007).

27 On the circumstances of this undertaking, and on Rousseau's chaotic initiation to science, see Van Staen (2010).

28 In a letter to his brother written on October 31st 1746, Frederic II of Prussia compared scientists such as Euler to the very useful but stern Doric style foundations of a palace, whereas the "philosophes" would represent the noble and decorative upper part of the same building (see *Correspondance de Frédéric II avec son frère Auguste-Guillaume*, Leipzig, s.d., p. 95).

Table 2: Formal structure of the "Republic of chemists" with an estimation of the number of scholars active between 1680 and 1890 i.e. born between the years 1640 (and still alive after 1700) and 1850.

	First rank / major scholars (A)	Second-string scholars (B)	Minor scholars / amateurs (C)
specialized (1)	Cl.-Louis Berthollet Humphry Davy 351	Nicolas Deyeux William Allen 1014	Séb. Matte; J.-F. Boulduc Rob. Mushet; Wil. Ch. Henry c. 2050
unspecialized (2)	Ampère James Hall c. 420	Gillet de Laumont Arthur Aikie c. 1200	Mrs Lavoisier François Delaroche c. 2500?
occasional (3)	Monge Diderot c. 1600?	J.-J. Rousseau c. 4500?	Mrs de Warens (c. 9200?)

cal Revolution", participation to the nascent "Republic of chemists" already required a regular practice of experimentation and the submission of empirical results to a scientific body, usually an academy. Making a career in the field further required consistent investigations, regular exchanges of information and publications. Affiliation to scientific academies, preferably one of the most prestigious of the time (Paris, London, Berlin, St. Petersburg, Stockholm, Bologna) would be the ultimate hallmark of a successful career. This road was still open to a few lawyers, landowners, officers or priests who were able to devote a substantial part of their life to research. For the others, securing a financially independent position in research, teaching or technical expertise required the help of efficient patrons and colleagues. Academicians of science were socially recognized figures, even by Jean-Jacques Rousseau, who did not hesitate to condemn most of scientific enterprises on moral grounds[30]. But even Lavoisier and Guyton de Morveau had started their careers as magistrates, which means that the difference between an amateur and a recognized man of science was often difficult to establish.

Being a chemist in the 18th and early 19th century: attempt at a formal definition

Two apparently opposed conclusions have been reached at this stage. One saying that the distinction between "philosophes" and true scientists became noticeable by the mid-18th century. The other that no clear-cut divide existed between, say a Diderot and a Venel, but a subtle gradation between different conceptions, or perhaps levels, of scientific practice. Major scholars, who trusted professional positions of researchers and academic affiliations, are often difficult to separate from second-fiddle scientists, who had a smaller output in publications and discoveries, and a more limited number of academic affiliations. A similar kind of continuum existed between scholars specialized in chemistry and those who practiced chemistry among other disciplines. Like botany, geology or meteorology, chemistry was still practiced by "men of letters" and amateurs, as it was on an occasional basis by scholars specialized in other fields of knowledge. Outlining the frontiers and subdivisions of an imaginary "Republic of chemists" is therefore a difficult task. Yet, the use of formal criteria may help to identify the most involved individuals, and further to set up some statistics.

A representative sample should at least include the two groups of formally identifiable chemists. The first group, that we may call A1, would include the specialized chemists of major importance, that is the chemists affiliated to at least two of the six major scientific academies of the 18th century, or who have their notice in the *Dictionary of Scientific Biography*[31]. 351 chemists active between 1700 and 1870 can be identified in this way (Table 2). A second group, that we may call B1, would include the specialized chemists considered of medium importance, which means affiliated to one of the six major academies of the 18th century, or included in Robert M. Gascoigne's *Historical Catalogue of Scientists* (1984)[32]. A further group of 1014 scholars active between 1700 and 1870 have at least one of these two characteristics.

By combining three degrees of importance, or scientific reputation (major scholars / minor scholars / amateurs), with three degrees of implication in chemistry (specialists / non-specialized scholars / occasional contributors), one can formally define a total of nine categories. The members of categories A1 and B1 are the only ones who can be systematically identified.

29 On Diderot's philosophical and literary connections to chemistry, see Pepin (2012) and Kawamura (2013).

30 Rousseau admitted that academicians could indeed be useful to mankind, as long as they did not behave like half-baked scholars, prompt to mischievous behavior in order to make a mediocre career in science, letters and arts. He believed that the role of educators of the human race should be left to minds of the caliber of Bacon, Descartes and Newton (*Discours sur les sciences et les arts*, § 59). This left no room for amateurs "à la Voltaire".

31 Gillipsie (dir.) (1970-1980).

32 Gascoigne (1984).

But with some patience and a good database[33], a significant proportion of unspecialized chemists (A2, B2) can also be listed. Many collaborated with specialized chemists and sometimes trained them. Further categories of chemists (C1, C2) can be identified, on a local basis, by applying a further set of formal criteria such as scientific publications, affiliation to a chemical society, presence in a scientific index (such as Poggendorff's *Handwörterbuch*[34]), teaching of chemistry, research performed in an institutional context, significant collaboration with a major chemist or possession of an important laboratory.

The analysis of the global network connecting these chemists, or at least those of the categories A1 and B1, requires to consider five possible kinds of links, that is:

- 1° The *epistolary links*, or the significant exchanges of information by letters. They have been treated above as a part of the "Republic of Letters". Such links have to be considered as "weak links" of information in the meaning of Granovetter[35], unless the exchange is more substantial than say 50 letters on either side (degree 3). Further investigations would require the availability of more inventories of correspondence, an item which is extremely rare in the field of chemistry.
- 2° The *training links* relating masters and students or assistants for various periods of time. They will make a substantial part of the ongoing analysis.
- 3° The *patronage links*, defined as successful recommendations of young chemists by patrons in order to secure them positions or at least significant research grants. As these patronage links are usually an extension of training links, they will be treated together in this article. In a significant number of cases, family connections are hidden behind these training and patronage links.
- 4° The *collaboration links* established by joint publications, "discoveries" or experiments performed in common. With the training and patronage links, they will make the other component of the present analysis.
- 5° The recorded *intellectual influences*, either materialized by the edition or the translation of a colleague's work or presented as crucial in biographic notices. Intellectual influences have a universal character within a given disciplinary field, contrary to training and collaboration links, which basically have a local and national character. They are therefore crucial to ensure the global coherence of a disciplinary field such as chemistry. Yet, they will not be detailed in this study.

On a broader scale, cross-cultural influences and translations ensure the circulation of empirical results and theories between the different portions of the international science system. This coordination was maintained throughout the 18th and 19th century despite the multiplication of national communities of chemists and the use of an increasing number of vernacular languages[36]. A closer investigation of this apparent paradox would probably validate the statement, which can be derived from Milgram's theory of the small worlds[37], that a small number of crucial connections between a limited set of major participants is enough to ensure the connection of the global system as a whole.
For the sake of the analysis, the complete set of actors of the period 1700 to 1870, whose career apex covered the period from 1680 to 1890, will be chronologically divided into four cohorts. The fourth cohort, grouping chemists whose careers reached an apex in the period 1860 to 1890, will not be fully included in the network study, since it would have required to register all their significant connections with the chemists of the period 1890 and 1914[38]. Fortunately, the year of the Karlsruhe international congress on chemical nomenclature (1860), represents a convenient – albeit arbitrary – dividing line between early modern and modern chemistry.

First period: the emergence of a set of specialized chemists (1680-1765)

The first of our periods stretches between the emergence of the first scientific academies in the late 17th century and the end of the Seven Years' War (1763), when enlightened States started to take an interest into the improvement of agriculture, manufactures, health and the management of their natural and social resources. Until then, they had focused on sciences and techniques more immediately connected to their military and naval needs: they showed more interest for astronomy, cartography or mathematics

33 My database includes more than 11.000 scholars active between 1700 and 1870.

34 Poggendorf (1863).

35 Granovettter (1973 / 1982). According to this theory, weak links can prove crucial for the introduction into a given field of research of information, concepts or theories from another field.

36 At least French, English, German, Italian, Swedish, Dutch, Russian, Hungarian, Czech, Polish, Spanish, Danish, and Portuguese.

37 Milgram (1967).

38 For symmetrical reasons, studying the links of the first cohort implied considering their connections with the 17th century scholars. But their limited number made the task possible.

than for chemistry. As a general rule, chemists of this period relied on informal training, or received an initiation to chemistry as part of their training in medicine or pharmacy. More precision can be gained from a representative sample of 142 specialists born between 1640 and 1725, 44 of them having the rank of major scholars. Trained between 1660 and 1745 or so, nearly half of them received a medical education. This was the case, for instance, of the famous Stahl and of his disciples. Another quarter had been taught pharmacy outside any university curriculum. The last quarter were educated either as mining engineers (for instance at the mining school of Freiberg in Saxony or at the *Bergskollegium* in Stockholm), or as military engineers (notably in France), but also in fields such as theology (for some German chemists), "arts" (in Great Britain) and even law (including Guyton de Morveau and Lavoisier in France). A small number of British chemists were self-taught[39].

As a consequence of the small number of formally trained chemists, the pattern of *training and patronage links* for the period gives the image of a low-density network, even within the major nations of France, Great-Britain, Germany and Sweden (Fig. 1). This graph clearly shows that Georg Ernst Stahl was the first to establish a school of chemistry in Halle (a university set up in 1694 by the Prussian government), even though chemistry was not formally included in his medical and philosophical teaching. Nevertheless, the links with his protégés were pretty strong, at least strong enough to lay the foundations of the Prussian school of chemistry. This school had its strongholds in Halle, where Johann Juncker taught medicine after Stahl, but also in Berlin, where Friedrich Pott and Caspar Neumann, both members of the Prussian Academy, were nominated in 1723 professors for chemistry and practical chemistry at the *Collegium Medico-Chirugicum*. Pott was the most active teacher of his generation, so that the main centre of German chemical training shifted in the early 1720s from the medical faculty of Halle to the Berlin *Collegium*. After 1733, Henckel's growing reputation as lecturer for metallurgical chemistry also attracted many students to the Mining academy of Freiberg. Among them were the Swede Anton von Swab, future co-director of the *Bergscollegium* in Stockholm, the famous Lomonosov, who created the first research laboratory in Russia, and the French pharmacist Jakob Reinhold Spielmann, who taught pharmacy, physiology and chemistry at the University of Strasbourg. In the second half of the 18th century, the main teachers of German chemists were Andreas Sigismund Marggraf and Rudolph Augustin Vogel, two disciples of Friedrich Pott. Marggraf became "pensionnaire" of the Berlin academy in 1738 and taught in its laboratory for nearly 30 years (1753-82). Vogel was called in 1754 to a full chair of chemistry in Göttingen.

[39] Unless stated otherwise, all statistical data are taken from my extensive database (see Sigrist (forthcoming 1). Most percentages have been calculated for the German, French and British chemists, who make about two thirds of Western chemists active between 1680 and 1890.

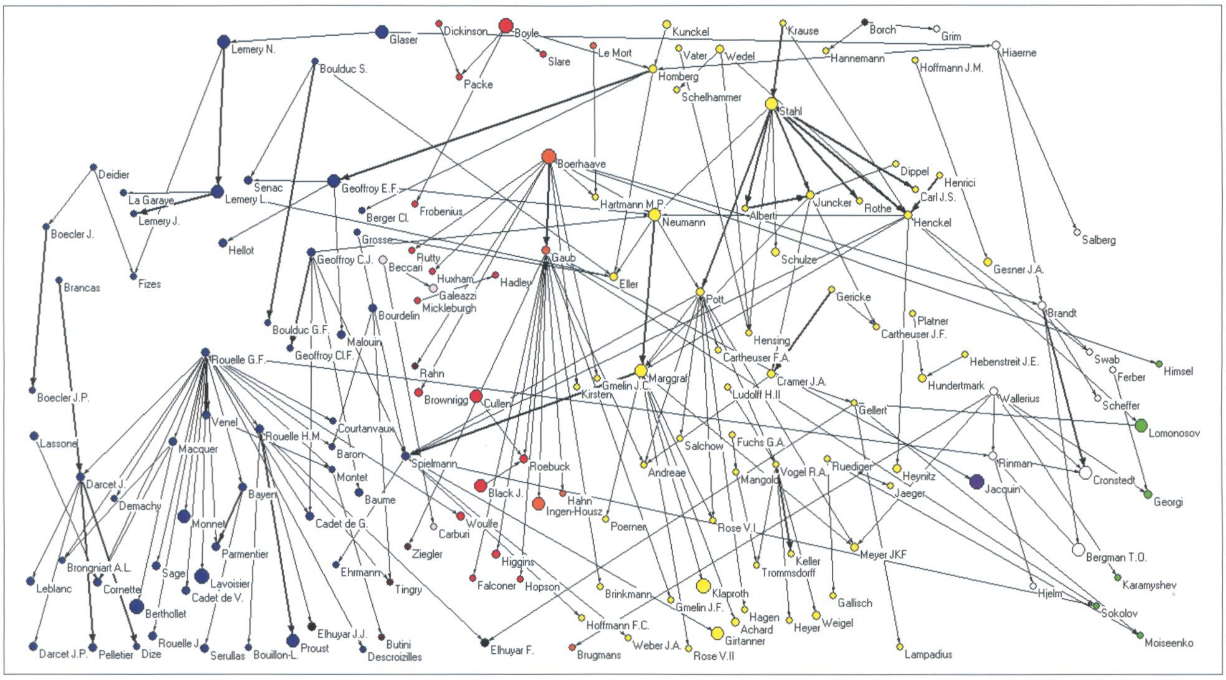

Fig. 1. Training and patronage links of specialized chemists (A1 & B1) for the period 1680 to 1765. Nodes for French chemists are in blue, British in red, German in yellow, Swedish in white, Russian in green, Dutch in orange, Italian in pink, Swiss in brown, "Austrian" in purple, others (Dane, Spanish) in black.

Another school of chemistry to emerge at an early stage was that of Leyden, where Hermann Boerhaave officially added chemistry in 1718 to his already successful teaching of medicine and botany[40]. His European fame, which probably matched or even surpassed that of Stahl, attracted would-be chemists from England (Rutty, Huxham, Brownrigg), Sweden (Brandt), Switzerland (Rahn) but also Germany (M. P. Hartmann, J. C. Gmelin, Kirsten) and even Kurland (Himsel). His disciple and successor Hieronymus Gaub, who taught between 1731 and 1775, also trained chemists from England (Cullen, Roebuck, Higgins, Falconer, Hopson) and Germany (Andreae, Brinkman, J. F. Gmelin) as well as a few fellow Dutchmen such as Jan Ingen-Housz, Johann David Hahn and Niklaus Joseph von Jacquin. After moving to Vienna in 1755, the latter would become the founding father of chemistry in the Habsburg Empire.

In France, the most successful chemistry teacher of the period was the already-mentioned Guillaume-François Rouelle, who remained in office between 1743 and 1768, and was succeeded by his younger brother Hilaire-Marin. With the exception of the above-mentioned Spielmann, an Alsatian trained at the German school, nearly all the French chemists of the mid-to-late 18th century were his disciples, or at least his students: Monnet, Macquer, Venel, Darcet, Parmentier, Lavoisier, Berthollet. His audience also included many amateurs less famous than Rousseau or Diderot.

Another group of chemists, established in Sweden, was specialized in mineral chemistry and metallurgy. Its importance derived from the quality of its members more than from their sheer number. At an early stage, it was based at the *Bergskollegium* in Stockholm, whose training laboratory was first headed by Urban Hiärne (1684) and then by Georg Brandt (1726). Its institutional basis later moved to the University of Uppsala, where a new chair of chemistry was created in 1750 for Wallerius, and attributed to Torbern Olof Bergman in 1767. Wallerius' audience was mainly composed of Scandinavians, but his reputation also attracted a few German, Dutch and Russian students.

Generally, the first half of the 18th century was a period of uncertain professional status for chemists. Most of them had complex career patterns, which usually combined two or three activities performed simultaneously. Most of these statuses were related to medicine, pharmacy, teaching or civil service, with a small proportion of research positions in scientific academies[41]. A significant number of chemists were landlords or priests, manufacturers or traders, lawyers, journalists or even craftsmen. Until the 1760s or so, chemistry was more often considered a craft than a science and its practice a matter for artisans more than for men of letters or scholars[42]. The limited presence of chemists in the epistolary exchanges of the Republic of Letters can be explained this way. Collaboration between chemists was further limited by the extreme variety of contexts in which chemistry was practiced.

After the triumph of Paracelsian and Helmontian physicians in the "antimony wars" of the 16th and 17th century[43], chemistry had become an auxiliary science of medicine and pharmacy. To governments, it was mainly a know-how designed to improve mining and metallurgy or the production of gunpowder. A number of chemists were also involved in the production of acids, dyes and other manufactured goods. Finally, only a very small number of natural historians or natural philosophers were "academic" chemists studying the four traditional elements (fire, air, water and earth), the metals, the vitrifiable and calcareous earths, the alkalis, the oils and of course the acids. Finally, the geographical dissemination of chemists over Northern and Western Europe and Italy was probably not a factor limiting *ad hoc* collaboration between chemists, but it certainly obliged most chemists to work in relative isolation and made their specialization more difficult. A few communities of specialists were grouped within major scientific academies (Paris, London, Berlin, Stockholm, St. Petersburg, Bologna), in a few university faculties or colleges (Leyden, Uppsala, Cambridge, Halle, Leipzig, Altdorf, Strasbourg, Montpellier) and in two or three mining centres (Freiberg in Saxony, Schemnitz in the Habsburg Empire, Darlana in Sweden)[44].

If one considers the *collaboration links* for the period from 1680 to 1765, the dominant impression is that chemists usually worked in isolation and rather seldom collaborated in an intensive or lasting way (Fig. 2). But the rarity of specialists can also have the reverse effect of inducing remote collaborations as happened in the late 17th century, when the very small number of qualified chemists incited them to collaborate across the Republic of Letters, sometimes moving to another country to find colleagues capable to contribute to their theoretical and practical investigations. The nucleus of an English group of chemists (Sloane, Frobenius, Hanckwitz and Friend) also appeared around Boyle and the Royal Society. Much later, by the middle of the 18th century, another group emerged in Northern England, around Prisetley, Watt, Warltire and Roebuck. Yet, the only group of chemists of the period with a significant cluster of collaborations was located in France. It first included mem-

40 Boerhaave, who lectured on medicine since 1701, had become professor of medicine and botany in 1709.

41 Sigrist (forthcoming 1).

42 Roberts (1993).

43 Debus (1977 / 2002) and Debus (2001).

44 Sigrist (forthcoming 1), Fig. 3

bers of the "Académie des Sciences" such as Lemery, Hellot, the two Geoffroys and Macquer, but later extended to chemists working on its margins, such as Baumé, Darcet and the Rouelle brothers. Finally, the nucleus of a Swedish group emerged around Brand, Swab and Cronstedt.

Second period: the "Chemical Revolution" (1765-1810)

The second period under consideration was marked by the theoretical and paradigmatic developments of the "Chemical Revolution", but also by the expansion of industrial applications of chemistry. It stretches from the end of the Seven Years' War to the foundation of universities in imperial France (1808-09) and in Berlin (1810). Chemists of this crucial period are represented by a sample of 217 specialists born between 1726 and 1770, of which 80 have the rank of major scholars.

One of the major characteristics of the period is the multiplication of training opportunities in pharmacy. As a matter of fact, 46% of future French chemists were trained as such (a Royal school of Pharmacy was even created in 1777) against 24% in medicine, even though less than half of them (i.e. 17% of French chemists) would later practice pharmacy as a profession. In the German States, pharmacy and medical education each represented one third (34%) of the training streams. Scientific education within "philosophy faculties" (or faculties of "arts" and sciences) was an option for 15% of German chemists. In Great Britain, the facilities provided by the Scottish universities and the London hospitals explain that 42% of chemists followed a medical education against 8% in pharmacy. A further 21% of British chemists were arts students in the traditional colleges of Oxford or Cambridge, and 6% were divinity students. Finally 15% followed an apprenticeship in a manufacture, an opportunity provided by the beginnings of the Industrial Revolution[45].

The creation of new institutions therefore increased the possibilities to train in chemistry, but subsequent career opportunities varied greatly from one country to another. In Germany, where the university system was the most developed, 33% of chemists of the period 1765 to 1810 were professors or teachers, an increasing proportion teaching chemistry instead of medicine. In France, the proportion of teachers was at a lower 25%, but their statuses improved significantly after the Revolution, which transformed many demonstrators into full professors. Even in England, the proportion of teachers reached 23%, thanks to the increasing interest for chemistry shown by professional corporations (physicians, pharmacists), by scientific societies and by the public at large. However, half of these teachers remained demonstrators, usually a very precarious status outside a few major hospitals in London, the other half reaching the more secure position of professor.

[45] Sigrist (forthcoming 1).

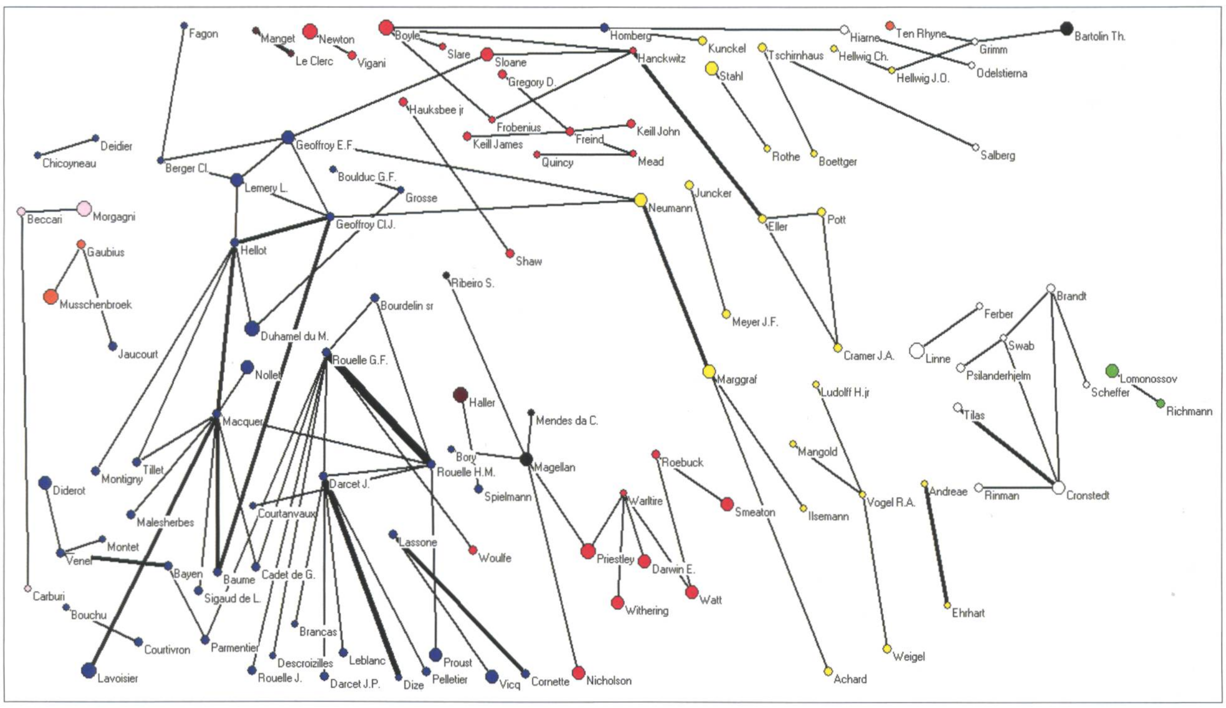

Fig. 2. Collaboration links between specialized chemists (A1 & B1) of the period 1680 to 1765. The colors of the nodes are the same as for Fig. 2 and all other figures.

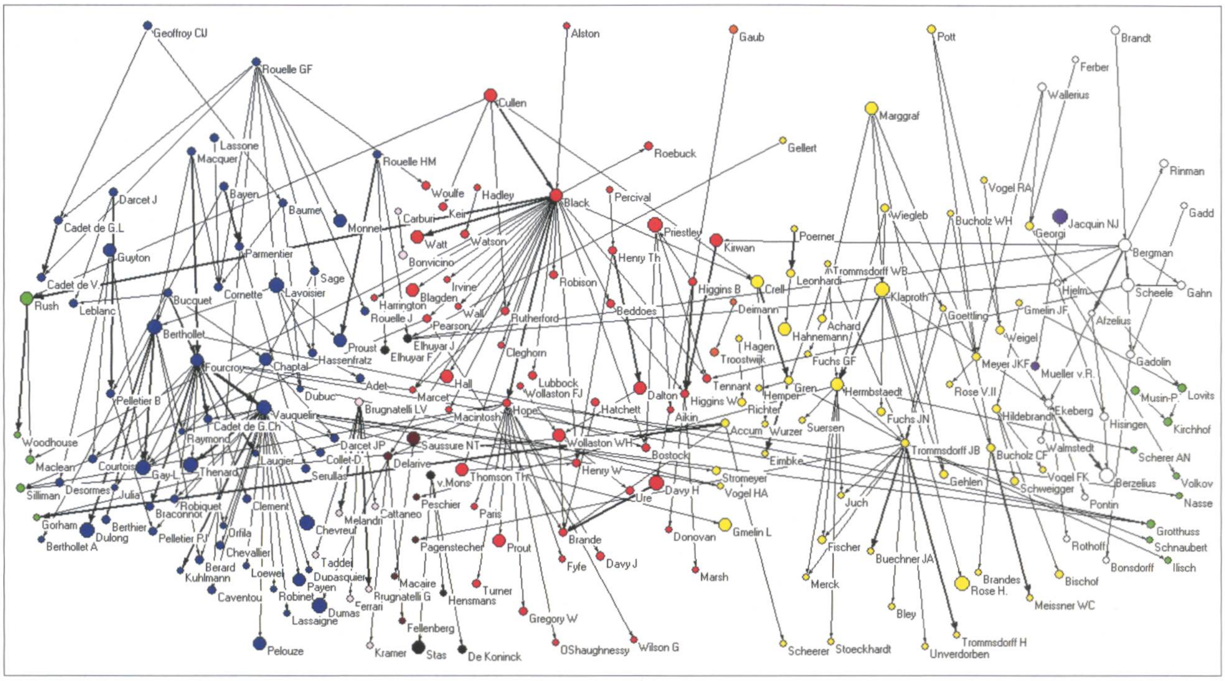

Fig. 3. Training and patronage links involving the major chemists (A1) of the period 1765 to 1810. Green nodes symbolize Americans chemists on the left side, and Russian chemists on the right side.

As a consequence, the *training and patronage links* knew an exponential development during the period 1765 to 1810. Because of that, my next graph is limited to recording the links implying the first rank chemists, that is the privileged group A1 (Fig. 3). This graph shows that Great Britain developed an important teaching tradition in chemistry after 1760, notably thanks to Joseph Black and Thomas Charles Hope, who successively taught at the University of Edinburgh between 1756 and 1843. Black, himself a disciple of William Cullen, was still representative of the old medical tradition, a science that he first taught for 10 years in Glasgow before moving to Edinburgh. Among his numerous students and disciples were many famous figures such as James Watt, Charles Blagden, James Hall, Thomas Thomson and his own successor Thomas Charles Hope. Foreign scholars such as the Americans Benjamin Rush and John Maclean or the German Lorenz Crell also came to Edinburgh to attend his lectures. After Black's death, his disciple Hope carried on the same general teaching for nearly half a century, training many British chemists (among them William Prout) as well as a few Americans (Benjamin Silliman, John Gorham).
In France, the teaching of Rouelle was still important at the very beginning of the period. Yet the most popular professors associated to Lavoisier's "Chemical Revolution" were Antoine-François de Fourcroy and Nicolas-Louis Vauquelin, even though Berthollet and Guyton de Morveau also trained a few notable chemists. Fourcroy, who started to teach in 1780 at the "Société royale de Médecine", became demonstrator for chemistry at the "Jardin du roi" in 1783 and full professor of chemistry at the "Muséum d'Histoire naturelle" in 1793. Vauquelin, who started his career as Fourcroy's disciple and assistant, became professor for docimasia at the "Ecole des Mines" in 1795, professor for chemistry at the "Collège de France" in 1801, professor for applied chemistry at the "Muséum" in 1804, and (simultaneously) professor for chemistry at the medical faculty of Paris in 1809. Beyond training the main French chemists of the next generation (Thénard, Gay-Lussac, Chevreul, Payen, Pelouze), Vauquelin was also the only one in France to attract foreigners as famous as Leopold Gmelin, Friedrich Stromeyer and Heinrich August Vogel, who would respectively become professors in Heidelberg, Göttingen and Munich.
In the German States, the main teaching positions were not limited to Berlin, even though Marggraf and Klaproth trained a few remarkable disciples, the first at the Prussian Academy, the second at the Mining School (est. 1770) and at the Artillery and Military Engineering School (est. 1787). Thanks to a few additional positions available in other institutions of the Prussian capital (Royal Pharmacy, *Collegium medico-chirurgicum*), Berlin became a favorable place for teaching and research in chemistry. Yet, an increasing number of chairs and lectureships in chemistry had also been set up at the universities of Giessen (1723), Helmstedt (1730), Erfurt (1740), Königsberg (1740), Duisburg (1742), Göttingen (1753), Ingolstadt (1760), Leipzig (1762), Heidelberg (1771), Greifswald (1774), Tübingen (1775), Halle (1783)

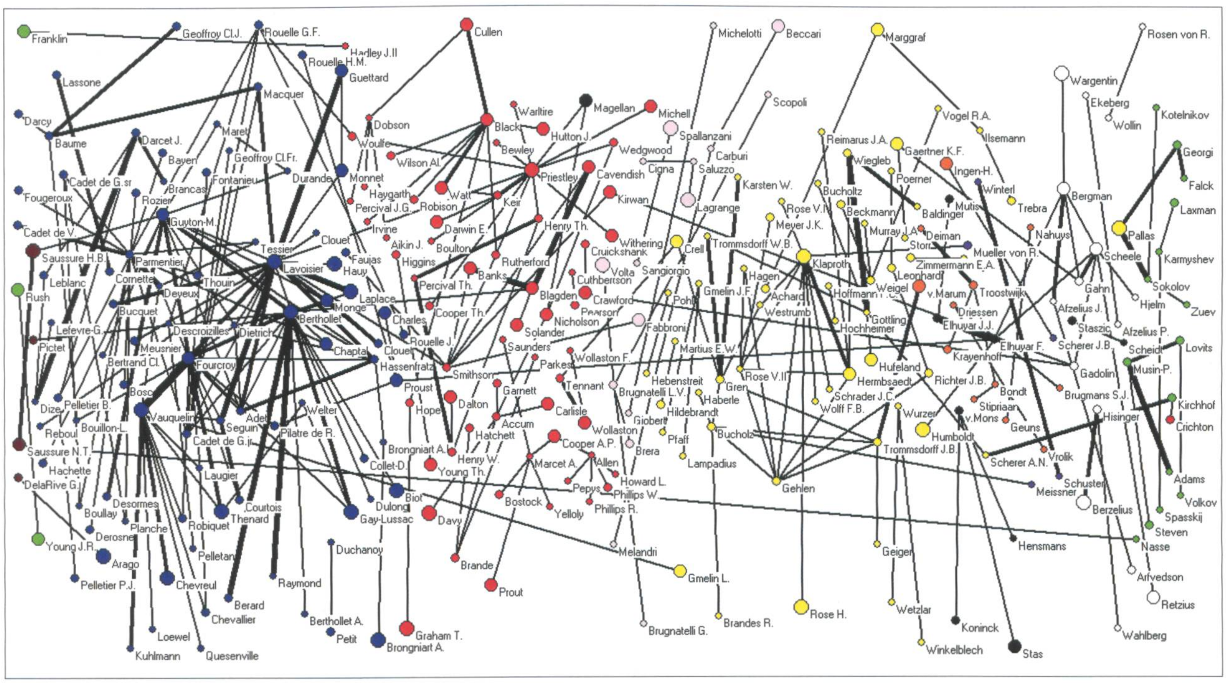

Fig. 4. Collaboration links between specialized chemists (A1 & B1) of the period 1765 to 1810.

and Erlangen (1796). Like Prussia, the Electorate of Saxony had its own mining engineers, chemistry and metallurgy professors, and specialists of china manufacturing. The duke of Brunswick established a chemistry professor in his *Collegium Carolinum* and a Board of Mines in Blankenburg, in the Hartz mountains. The neighboring State of Hanover had its own school of mines in Clausthal, close to Blankenburg. In the last two decades of the 18th century, boarding schools for young chemists were created in Langensalza (1779), Berlin (1789) and Erfurt (1795).

These new opportunities had consequences which are not always visible on our graph, centered on first rank chemists. In this category, the most eminent German pedagogue of the period was the pharmacist Johann Bartholomäus Trommsdorff, whose boarding school in Erfurt was the most successful of its kind. Among the second-rank chemists who had a crucial role as teachers, one should mention Johann Friedrich Gmelin in Göttingen, who trained about 20 chemists with a reputation, mostly German but also Swiss and Russian. Another successful teacher was Johann Friedrich Göttling, who taught chemistry and technology in Jena between 1789 and 1809, and trained about 12 chemists included in our database, mostly from Germany.

In Sweden, Torbern Olof Bergman, who taught chemistry and pharmacy at the University of Uppsala between 1767 and 1784, totally eclipsed the *Bergskollegium* as training centre for chemists. The same can be said of Anders Gustaf Ekeberg, who taught chemistry at Uppsala between 1794 and 1813, besides his own master Afzelius.

Italy, which had not been able to set up chemistry as an independent science in the first half of the 18th century, had its first significant chemistry teaching established at Pavia, under Austrian rule, in 1796. Despite many political changes, Luigi Valentino Brugnatelli, the first holder of the chair, succeeded in training there a few significant chemists who would implement the discipline at other Italian universities. The famous Dutch school of Boerhaave and Gaub vanished after 1760, long before Gaub had stopped teaching. But Jean-Baptiste Van Mons, himself trained as a pharmacist, established what would later be the nucleus of a Belgian school of chemistry including Stas, De Koninck and Hensmans.

As for the Swiss, they mainly used the facilities provided by the German and English institutions. The nucleus of a small Genevan school was nevertheless established by Nicolas-Théodore de Saussure and by Gaspard Delarive, who had the privilege to be the first chemistry professor of the famous Jean-Baptiste Dumas.

Considering the *collaboration links* of chemists for the same period, it appears that the loosely connected entity of the early 18th century has been suddenly transformed into a highly structured community, at least at the national level (Fig. 4).

The connections were especially dense in France between the main actors of the Chemical Revolution: Guyton-Morveau, Lavoisier, Berthollet, Chaptal, Fourcroy and Vauquelin, but also Gay-Lussac and Thénard. It is to be noted that these close connections included Monge and Laplace, who were not chemists. The members of this densely connected set were all living in Paris and working in institutions of a national character, mainly the "Académie des Sciences", which became in 1795 the first class of the "Institut de France". A closer look at these connections, made easier by the removal of all the collaborations of a lower degree (the figure is not given here), shows the existence, besides the main set of members of the "Académie des Sciences", of two smaller groups of specialized chemists. One included pharmacists such as Parmentier, Cadet de Vaux, Deyeux or even Thouin. The other brought together technicians or manufacturers such as Darcet, Brancas, Dize, Pelletier and Leblanc. The obvious conclusion is that even if chemistry emerged as a true science of natural materials, with its own disciplinary paradigm, a convenient space was also left for research of a practical or applied nature[46]. New investigations on air healthiness (eudiometry) and hospital hygiene, on artificial mineral waters, on food production (bread, soups, sugar), on drink control (water, wine, spirits, milk, syrups), on public lighting could still be relied to the tradition of medical-pharmaceutical chemistry[47]. The craftsmen's and manufacturing tradition of chemistry also developed new processes for the production of acids, soda, bleach and their derivatives (dyes, glass, soap). The productions of gunpowder, alloys and paper also became more efficient.

On the professional level, members of the "Académie des Sciences" trusted most positions and sinecures available to chemists, which were equivalent to a total of 25 to 30 full-time positions just before the Revolution[48]. Academicians, either fully pensioned or not, obviously had the best opportunities to become director of royal manufactures such as Sèvres (china), the Gobelins (tapestry) or St-Gobain (glasses), and the greatest chances to be appointed to one of the permanent technical inspections (of mines, pharmacies or mineral waters). Other positions available to chemists existed in the main hospital pharmacies, within the Faculty of medicine and the College of pharmacy, at the Veterinary school of Alfort, at the "Collège Royal" (later "Collège de France"), at the Royal Mint or at the "Régie des Poudres". All these positions, reinforced after the Revolution, contributed to set up the nucleus of a national community of professional chemists. Pharmacists and physicians, either military or civilians, lost the professional supremacy they had in the previous period, but they still represented respectively 17% and 8% of French chemists of this period[49]. Manufacturers were a smaller group of about 10% of the chemists. Finally, amateurs remained a major component of Enlightenment chemistry: even within the group of formally defined French chemists, some 14% had no professional connection with chemistry. They belonged to the social elites of the "Ancien Régime" (lawyers, landlords, retired officers and priests).

Great Britain also showed the coexistence of two or three groups which had not only different professional characteristics, but also different geographical locations. One group, gathered around Black, Cullen and Watt, had an obvious Northern England and Scottish location. The same was true for the group built up around Priestley, which had an even more industrial focus. Another group including Blagden, Banks and Cavendish had a Londonian and elitist colour, testifying that chemistry had become a new component of a gentlemanly scientific culture so typical of the Royal Society[50]. On a closer look, it appears that the Northern England-Scottish group (James Watt, Joseph Black, William Cullen) gave the example of an association between manufacturers and university professors. The dissenting pastor Priestley was for his part linked to a Midlands group of physicians, pharmacists, manufacturers and teachers (Percival, Thomas and William Henry, John Dalton). Like Dalton, they considered themselves more professional than their Londonian colleagues, who belonged to a social elite of physicians and leisured gentlemen. Generally, physicians represented 31% of the British chemists of the period, whereas lawyers, landlords and other gentlemen made 21% of this community. Together, they provided more than half of the British chemists, and they massively contributed to maintaining close links between natural philosophy, medicine, chemistry and gentlemanly culture in general.

In the German States, the larger group, centred on Klaproth, Hermbstaedt and Valentin Rose Jr, was mainly composed of Prussian chemists working in Berlin. Another group linked chemists from different cities and States such as Bucholz, W. B Trommsdorff and J. B.Trommsdorff in Erfurt (ruled until 1802 by the Archbishop of Mainz), Gren in Halle, Gehlen in Berlin and Munich. Like many German chemists since the late 1770s, they published most of their articles in Friedrich von Crell's periodicals, which became the focus of an emerging national school of chemistry, characterized by a prolonged opposition to the "French chemistry" of Lavoisier[51]. Part of this resistence may be explained by the fact that 30% of German chemists of the period were pharmacists, whose interests were more practical than theoretical[52].

46 The importance of pharmacy in the Chemical Revolution has been advocated by Simon (2005).

47 On the connections between chemistry and public health in 18th century France, see Debyser (2007, p. 257-284).

48 This is at least the number of positions occupied by the chemists of our sample.

49 Sigrist (forthcoming 1).

50 On the social roots of 18th and early 19th century chemistry in Great Britain, see Golinski (1992).

51 Hufbauer (1982).

52 On German chemists with a pharmaceutical background see Klein (2007).

In Sweden, a group of chemists also appeared to coalesce around Bergman, Scheele, Gahn and Gadolin. This closer association between members of the *Bergskollegium* in Stockholm and professors at the University of Uppsala potentially gave to this group a national dimension perfectly in line with the aims of the Stockholm Academy of Sciences. Finally, various small groups of chemists existed in Italy (pink), in the Netherlands (orange) and in Russia (green).

The overall conclusion is that despite the intensification of scientific collaborations in the second half of the 18th century, significant international collaborations remained pretty rare except in countries such as the Netherlands, Switzerland, "Austria" or Spain, whose local communities of specialists were perhaps too small to be really autonomous.

Third period: professionalization and the rise of organic chemistry (1810-1860)

In this survey of emerging chemical networks, the third period, marked by a growing professionalization and the emergence of organic chemistry, stretches from the creation of the University of Berlin (1810) – and the wake of Prussian and German nationalism – to the first international congress of chemistry in Karlsruhe (1860), which was indeed a milestone in the development of international collaboration between chemists. The chemical community of this period is represented by a sample of 461 specialists born between 1771 and 1820, of which 129 have the rank of major scholars.

After the Revolutionary and Napoleonic wars, the increasing demands for trained chemists explain the creation of many teaching positions, so that the proportion of teaching chemists reached 41 % in the German States, 42 % in France and 35 % in Great Britain[53]. Yet, the realities behind these proportions were very different from one country to another. Germany, whose university system had gradually evolved in the previous periods, did not suddenly create a lot of new teaching positions in universities, but most chairs of chemistry were transferred from the medical to the "philosophy" faculties and equipped with good teaching laboratories. Bookish teaching of chemistry was abandoned in favor of a more comprehensive approach combining theory and practice. After 1830, more chairs for chemistry were created within a new kind of technical schools (*Technische Hochschulen*). Even industrial and business schools (*Gewerbeschulen*) as well as secondary schools (*Realschulen*) were equipped with combined chairs of chemistry and physics, or of chemistry and natural sciences. The creation of agricultural and forestry institutes was another striking feature of the period in Germany.

In France, the institutions established by the Revolution and Napoleonic regimes were completed by the creation of the "Ecole Normale Supérieure" (1826) and the "Ecole Centrale des arts et manufactures" (1829). In Great Britain by contrast, one third

53 Sigrist (forthcoming 1).

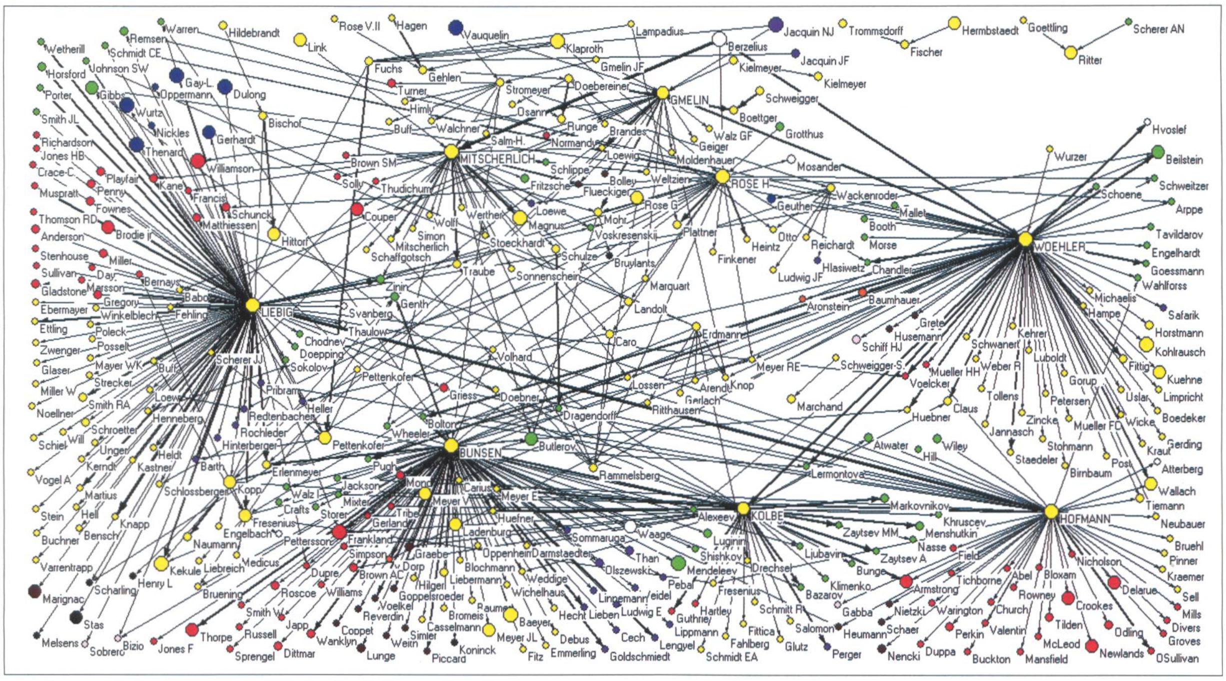

Fig. 5. Schematic view of the training and patronage links involving the major German chemists (A1) of the period 1810 to 1860.

of the teaching chemists were still demonstrators or lecturers with lower status, despite the campaigns launched after the creation of the *British Association for the Advancement of Science* (1831). Half of the teaching chemists were lecturers who worked in hospitals or medical schools, for learned societies or for agricultural, industrial or pharmaceutical associations, not to mention the usually private Mechanics' Institutes. The other half lectured in universities, technical colleges or institutions such as the Royal Institution or the Royal College of Mines.

All these new teaching positions massively favored the development of *training and patronage links*. This development was exponential, so that a visual representation of these links, even limited to the German chemists of major importance (A1) and drawn in a schematic way, stretches the readability of any graph to its limits (Fig. 5).

In the first third of the 19th century, Prussia created teaching positions for chemists in its new universities of Berlin (1810) and Bonn (1818), in Breslau (1813), at the Veterinary School and the *Gewerbe-Institut* in Berlin (1819 and 1821), as well at the Prussian Board of Manufactures (1818). Curiously enough, the major change in teaching methods did not happen in Prussia, but in the small University of Giessen, in the duchy of Hesse-Darmstadt. There, Justus von Liebig, one of Humboldt's protégés who had spent some time in the laboratory of the Ecole Polytechnique in Paris, became chemistry professor in 1826. A few years later, he transformed his small laboratory into a major teaching institution, first intended for pharmacists. To match this achievement, the neighboring electorate of Hesse, who had introduced chemistry in its University of Marburg (1805)[54] and in its Artillery and Engineering school in Cassel (1811), soon set up a similar teaching laboratory for Robert Bunsen (1839). Bavaria, where a policy of scientific and industrial development had been set up in the late 18th century, established new pensions for chemists within its Academy of Science in Munich, and created chairs of chemistry at the universities of Landshut (1807) and Würzburg (1828) as well as in the Polytechnic Institute of Augsburg (1808). The University of Munich, established in 1826, would be honored to recruit Liebig in 1852, even under the condition of his being discharged of teaching duties. For his part, the new duchy of Baden, who had inherited the university of Heidelberg in 1803 and the university of Freiburg in 1805, recruited Leopold Gmelin (1817) and Bunsen (1851) in Heidelberg and established a chemistry chair with a modern laboratory in Freiburg (1820).

Thanks to the establishment, between 1820 and 1840, of a small number of improved training centres, Germany soon became the European hothouse for breeding outstanding chemists. Liebig is generally credited with the invention of the training system combining theory in the auditorium and practice in the laboratory. In fact, he rather extended on a quasi-industrial scale a system conceived by many forerunners since the mid-eighteenth century[55]. His method would soon be reproduced by Heinrich Rose in Berlin (1835), by Friedrich Wöhler in Göttingen (1836) and by Robert Bunsen in Marburg (1839). Before being generalized after 1860, it would also be exported by some of his disciples to Edinburgh (William Gregory, 1844), London (Hofmann, 1845), St. Petersburg (Zinin, 1848), Oslo (Adolf Strecker, 1851) and Ghent (Kekulé, 1858).

Evan before Liebig's innovations, future British chemists had started to attend the German universities. Apparently, the movement started by the mid 1820s, when a few students, dissatisfied with the mediocre training opportunities available in their own country, attended chemistry lectures given by Mitscherlich at the newly created University of Berlin. A few years later, they started to move on a larger scale to Liebig's laboratory in Giessen, and from 1840 onwards to Robert Bunsen's in nearby Marburg. To counter this tendency, the British government, under pressure from the British Association for the Advancement of Science, established in 1845 the Royal School of Chemistry, whose first professor was August Wilhelm von Hofmann, a German disciple of Liebig.

In Russia, the practice of importing German pharmacists and chemists had been a tradition in the 18th century. It was still alive in the 1820s and early 1830s, as is shown by the examples of Karl Friedrich von Schlippe and Carl Julius Fritzsche, two disciples of Mitscherlich who made a career in Moscow and St-Petersburg. Yet, Russians had been often disappointed by the poor quality of some German chemists or by their weak commitments to Russian interests. It was therefore decided in 1828 to train indigenous chemists first in Russia before sending them to study in German laboratories for two years or more. Most of these first recruits went to Friedrich Wöhler in Göttingen. A few also worked in Liebig's laboratory in Giessen or in Bunsen's in Marburg. After 1850, some Russian chemists, who by then enjoyed com-

53 Sigrist (forthcoming 1).

54 One year earlier, the Electorate of Hesse had created its own Institute of Mining Sciences in Cassel.

55 Demonstrations of chemistry were already practiced, before 1750, by Brandt at the *Bergskollegium* in Stockholm and by Rouelle at the "Jardin du roi" in Paris. For pharmacists, theoretical and practical training was combined at the Royal School of Pharmacy in Paris (1777) and at the pharmaceutical boarding schools of Langensalza (1779), Berlin (1789) and Erfurt (1795). At the university level, Wallerius and Bergman, who taught in Uppsala after 1750, already used to open their laboratory to the students. In the first quarter of the 19th century or so, practical training in university contexts was set up by Gadolin in Abo (1797), by Berzelius at the *Karolinska Instituet* in Stockholm (1807), by Stromeyer in Götttingen (1817), by Thomas Thomson in Glasgow (1818) and by Edward Turner in Edinburgh (1824).

fortable subsidies from their government, started to combine attendance to two or three German universities with training courses in Paris. Yet their most popular destination clearly became Marburg, where Hermann Kolbe had succeeded Bunsen in 1851, before moving to Leipzig in 1865.

A third important group of chemists trained at the German universities were the Americans. Their favorite destination was Giessen (Liebig), although quite a few went to Göttingen (Wöhler) and to Marburg (Bunsen), sometimes even in successive stages. Because of the absence of financial help from their government, their travel across the Atlantic was a heavy investment. In order to make it more profitable, they frequently attended courses and laboratories in France as well as in Germany.

The next group to be considered was made of citizens of the Habsburg Empire dissatisfied by the teaching provided in Vienna by Josef Franz von Jacquin and Paul Traugott Meissner. They sometimes paid a visit to Liebig's laboratory in Giessen but their favorite destination was Robert Bunsen's laboratory in Marburg. Curiously enough, the two founding fathers of chemical teaching and research in the Austrian empire, Anton von Schrötter and Josef Redtenbacher, made other choices: the first went to Liebig after studying under Jacquin and Scholtz in Vienna; the second, who had also studied under Jacquin, went then to Heinrich Rose in Berlin and later to Liebig.

A last significant group was made of Swiss chemistry students, who, with the help of a consistent number of exiled German chemists, would become the spearhead of an industrial revolution in their own country. They had a very strong preference for Bunsen in Marburg, even though a few visited Hofmann in London or Wöhler in Göttingen. A striking feature of this emerging community is that about one third of it consisted of Germans. It is true that a small number of Swiss-born chemists went in the opposite direction and choose to make a career in Germany.

Statistics limited to German professor of chemistry of major importance indicate that they trained slightly more foreign chemists of some reputation (52%) than nationals (48%), a proportion which is surely not representative of the whole reality of German universities[56]. This proportion, valid for the five or six major German universities, nevertheless compares favourably to the 37% of foreign chemists trained in the major Parisian institutions. The French chemists, who had proven their usefulness under the Revolution by improving the production of gunpowder, had of course been granted quite a few positions in the following years. Chairs of chemistry had been created at the "Ecole Polytechnique", at the "Muséum", at the "Ecole des Mines", at the School of Pharmacy, at the School of Medicine, at the "Conservatoire National des Arts & Métiers", and after 1808 at the university faculties of science and medicine. These institutions, nearly exclusively concentrated in Paris, had been calibrated to the needs of the French State in a uniquely coordinated system. It provided an ample supply of training opportunities for students interested in chemistry, and especially in pharmacy. Chemists trained in high technical schools or in universities made a smaller proportion of 27% (they were 9% before the Revolution), that is much less than the 39% of German chemists trained in universities. In a way, the political divisions of the German nation may have produced a surplus of chemistry professors, and therefore a very strong financial incentive to accept foreign students in potentially under-populated faculties. Training in pharmacy made another significant difference between France and Germany: if 40% of the French chemists of the period 1810 to 1860 were still trained as pharmacists, only 29% of German chemists followed the same training path.

In Great Britain, the training of chemists was first adjusted to the needs of the medical profession through a complex set of local institutions. In the early 19th century, 34% of British chemists were trained in medicine against 20% in France and 18% in Germany. Later on, the needs of industry became preeminent. As a result, only 21% of British chemists followed a university curriculum in science, often at a German faculty. Classical training in a college of arts was still the fate of 14% of British chemists. As before, training in pharmacy was marginal (7%).

A graph depicting the *links between masters and disciples* can only confirm that the French chemists heavily depended for training on the Parisian "grandes écoles", even after the creation of a national university system in 1808-09 (Fig. 6).

In the early 19th century, quite a few French chemists were trained by Nicolas Louis Vauquelin either at the "Muséum" or at the Medical faculty. A still greater number followed the lessons given by Louis Jacques Thénard at the "Collège de France", at the Science faculty (Sorbonne) and at Polytechnique. These lessons were often combined with Joseph-Louis Gay-Lussac's at Polytechnique, at the Science faculty and later at the "Muséum". Thénard and Gay-Lussac indeed cumulated prestigious teaching positions in the same way than their masters Berthollet, Fourcroy and Vauquelin had done before. Among their successors, the most charismatic figure was Jean-Baptiste Dumas, who taught chemistry since 1829 at the newly created "Ecole centrale des arts et manufactures", at Polytechnique, at the Science faculty and at the Medical faculty. He was even able to cumulate all four positions for at least 12 years (1841-52)! In this crucial position, he trained most of the

[56] Obviously, less famous chemists working in smaller universities trained a much higher proportion of German chemists.

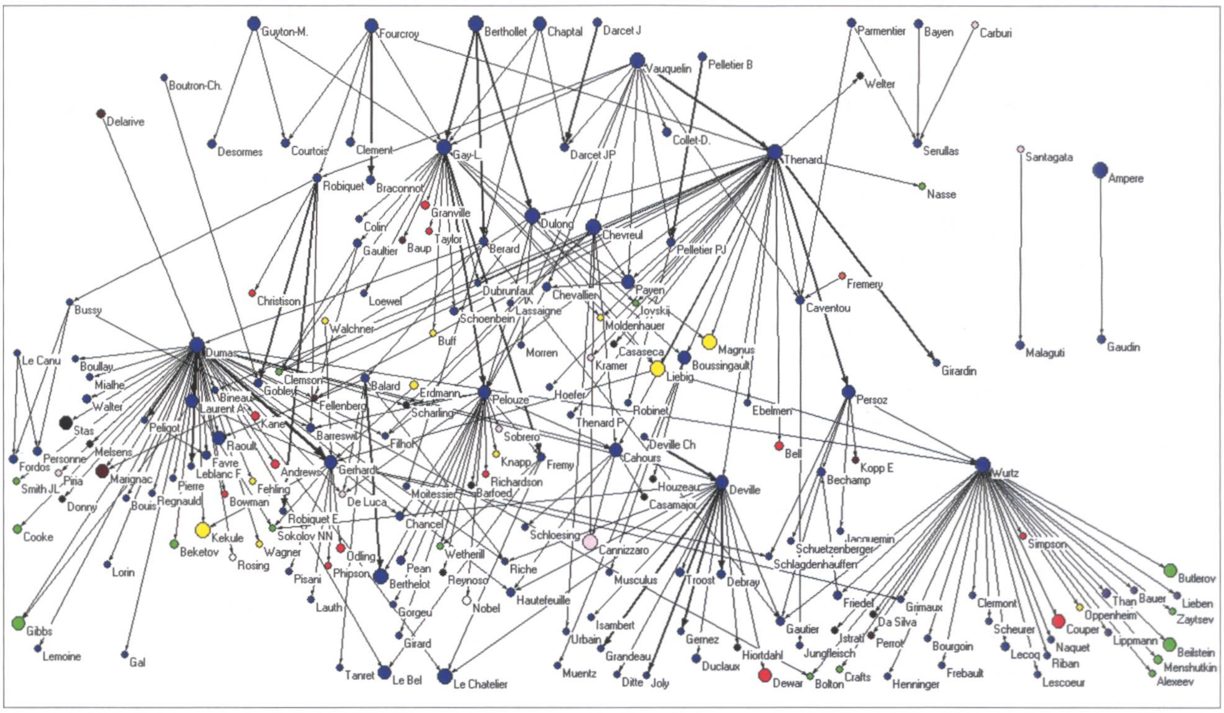

Fig. 6. Training and patronage links involving the major French chemists (A1) of the period 1810 to 1860.

next generation of French chemists (including Wurtz, Deville, Gerhardt, Laurent, Le Bel, Raoult), as well as a significant number of Americans (Gibbs, Cooke, J.L. Smith), Belgians (Stas, Melsens, Donny), British (Kane, Andrew, Bowman) and even Germans (Kekulé, Wagner, Fehling).

Michel Eugène Chevreul, who succeeded to his master Vauquelin at the "Muséum" in 1830, was a much less successful teacher, although he remained in office until his death in 1889. On the other hand, Théophile Jules Pelouze, another of Vauquelin's protégés who had a relatively short teaching career at Polytechnique and at the "Collège de France" (1837-51), trained a consistent group of chemists including Cahours, Barreswil, Frémy and Berthelot.

At the next generation, the most successful professor was Charles Adolphe Wurtz, who was, together with Gerhard, one of the few French disciples of Liebig. His reputation also attracted some important foreign chemists, notably from Russia (Beilstein, Butlerov, Menshutkin, Zaytsev, Alexeev) and from the Habsburg Empire (Than, Bauer, Lieben, Lippmann). But the period when major patrons cumulated many teaching positions was over. For most of his career, Wurtz held a single chair at the Medical faculty, and only added a second chair at the Science faculty after 1874. In a period of growing specialization, he also focused on organic chemistry. His contemporary Henri Sainte-Claire Deville was specialized, for his part, in mineral chemistry and remained faithful to his chair at the Science faculty (Sorbonne). In a time when the developments in organic chemistry seemed more promising than the possible achievements in mineral chemistry, Deville's fame as a teacher, and his ability to attract foreign scholars, never matched those of his colleague Wurtz.

Between 1810 and 1860, the number of *collaborations* increased in such an exponential way that any visualization on a single graph becomes impossible. This is the clearest sign that chemistry was structuring itself as a collective research enterprise and as a discipline at the national level, but increasingly also at an international level. A census limited to the very intense or lasting collaborations gives an outline of the changing collaborative pattern of the period (Fig. 7). The resulting figure immediately shows a clear-cut division between the period before the 1830s (upper part of the graph) and the period after 1840 (lower part). This translates the clear intensification of chemical collaborations that happened after 1840, that is after the generalization of laboratory training at the German universities.

Until the 1830s, the French chemists built the most integrated set of specialists, around such figures as Vauquelin, Thénard, Gay-Lussac or Pelletier. At the same time, the interconnections of English chemists were mainly Londonian, and more precisely hosted by the Royal Institution where Davy, Faraday and Brande performed various functions. In the German States, Berlin was the dominant centre in the early 19th century, thanks to Adolf Gehlen, editor of the *Neues allgemeines Journal der Chemie* and later

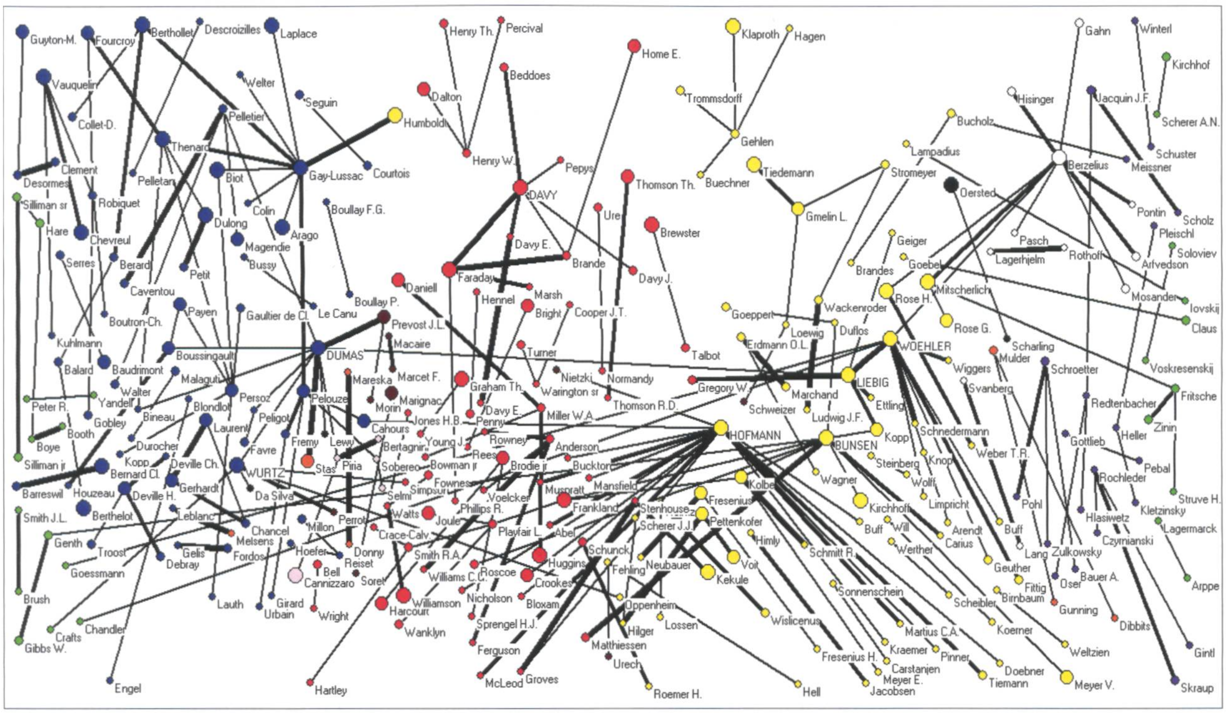

Fig. 7. Most lasting or most intensive collaboration links between specialized chemists (A1 & B1) of the period 1810 to 1860.

to Eilhard Mitscherlich and Heinrich Rose. Yet, another group, gathered around Leopold Gmelin, linked scholars from the universities of Heidelberg (Gmelin, Tiedemann, Löwig) and Göttingen (Stromeyer). It has to be noted that quite a few German chemists made a career abroad, in Russia, in England, in the United States or in Switzerland, but curiously enough not in the Habsburg Empire. Their French and British peers were usually less interested in leaving their own country. Swedish chemistry (in white on the right of Fig. 7) seemed to experience a new golden age in the early 19th century, thanks to Jöns Jakob Berzelius and the creation in 1807 of the *Karolinska Instituet* in Stockholm. Berzelius' influence on the Prussian chemists Mitscherlich and Rose, and on Wöhler in Göttingen, is also clearly visible.

The landscape of chemical collaborations dramatically changed in the 1830s with the development of organic chemistry, that radically enlarged the field of empirical investigations and therefore the need for collaborative research. Liebig, who was the major agent of this change, had nevertheless relatively few very intense or very lasting collaborations with his disciples, except for Kopp. His pupils were probably too numerous to be kept a long time in his laboratory in Giessen. For long-term collaborations, Liebig relied preferably on colleagues such as Wöhler in Göttingen or William Gregory in Edinburgh. His collaboration with Jean-Baptiste Dumas on the theory of radicals, although of a less lasting character, was an epoch-making one. It was therefore left to chemists such as Wöhler, Bunsen, Hofmann and Kolbe, but also Fresenius and Pettenkofer, to transform some of their training relations with disciples into intense or lasting research collaborations. The increased use of laboratory assistants was a direct consequence of the new research programs associated with the development of organic chemistry. Besides the traditional peer to peer collaborations, this generated enhanced opportunities for lasting collaborations with former students. And as some of them came from abroad, the frequency of transnational collaborations also increased, especially between German and British scientists.

The French community of chemists, which had been the most interconnected since the Enlightenment period, did not experience such a sudden transformation, probably because more job opportunities existed outside the world of research in chemistry. Nevertheless, the traditional accumulation of teaching positions by a few major figures, which were more or less able to control the evolution of the discipline at a national level, gave way after 1840 to a more specialized structure of teaching and research. Instead of a mixture of peer to peer and master-disciple relations, with a strong national character, collaborations between masters and disciples clearly took the upper hand. This is a sign of growing specialization, which made the emergence of rival schools more likely, even within the same country (Wurtz versus Deville in France, but even more clearly Bunsen versus Wöhler or Hofmann in Germany). The period after

1840 saw the emergence in France of leading research centres under the direction of Jean-Baptiste Dumas (Polytechnique, Medical faculty), Charles Adolphe Wurtz (Science faculty), Théophile Pelouze (Polytechnique), Jean-François Persoz (Strasbourg) and Henri Sainte-Claire Deville (Medical faculty).

On the international level, Dumas and Wurtz were able to develop some intensive collaborations with chemists from "smaller" countries such as Italy, (Pria, Sobrero), Belgium (Stas, Melsens), Switzerland (Prevost), Denmark (Lewy) or Portugal (Da Silva). By contrast, German chemists developed intense collaborations with disciples from the United States (in the case of Wöhler and Bunsen) and from Russia (in the case of Mitscherlich and Lampadius).

In England, the German university system was in a way imported in 1845, when Hofmann was put in charge of the new Royal College of Chemistry in London. The intense and multisided collaborative network he developed during his 20 years in England did cast a shadow over smaller groups, such as those built around William Allen Miller at King's College in London, Thomas Anderson at the University of Glasgow and Lyon Playfair at the University of Edinburgh. Returning to Germany (1865), Hofmann transformed the chemical laboratory of the University of Berlin into one of the two main centres of chemical collaboration in the country, the other being in Leipzig. Whether his years in England did play a role in this change cannot be established on the basis of a simple network study.

Italian chemists (pink nodes on Fig. 7) and their Dutch colleagues (orange nodes) showed little ability to develop intense or lasting collaborations. By contrast, chemists working in Russia (green nodes on the right), in the United States (green nodes on the left) and even in the Habsburg Empire (purple nodes) showed a greater ability to develop their own collaborative traditions. The "imperial Austrians" in particular, a term which includes the Hungarians, the Czechs and some of the Poles, had little connections with the outside world and developed their own school(s). Yet, most of their chemists were of second-rank importance, whereas Russia and the United States would soon produce quite a few chemists of major importance.

The main conclusion which can be driven from this survey of the most intense and lasting collaborations is that the increased intensity and frequency of collaborations was mainly due to the creation of the new laboratory facilities in the German universities and in the French "grandes écoles". Therefore, the next question to examine is whether such collaborations could also develop in a less institutionalized context such as the one prevailing in Great Britain, where scientific societies, medical schools and industrial corporations still played a major role until 1860.

In the previous period, the apparent scarcity of available positions in Britain had not prevented its community of chemists to develop in a spectacular way. Part of this was due to the industrial revolution, which meant the development, after 1760 or so, of mines, steelworks as well as of manufactures of glass, printed calicos, dyes, soap and vinegar and of course chemicals (acids, alkalis, magnesia). Another part was due to the growing interest for chemistry within the cultivated circles of the capital, the dissenting circles of the Midlands and among the physicians all over the country[57]. Very emblematic of this social and intellectual context was the creation, in 1799, of the Royal Institution, aimed at spreading the interest for chemistry to a wider audience, which in fact meant the social elite of the capital. A certain number of new positions of lecturers were also created in the London hospitals, in medical schools and in some military colleges. Yet, the number of chemistry professors remained relatively low in Oxford and Cambridge, and even in Scottish universities. This is the reason why a growing number of British students in chemistry attended German universities.

In the early 19th century, chemistry, which had been so far considered as a practical know-how in England, became a true science in which theoretical knowledge took an increased importance, even for industrial and agricultural applications. Yet, the creation of the London Institution for the Promotion of Literature and Useful Knowledge (1806) would not bear all its fruits before the 1860s and 1870s, when it became an important centre for chemical research. Even the establishment in 1845 of the Royal College of Chemistry (renamed Royal College of Mines in 1853) did not substantially modify the institutional landscape of British chemistry, which remained composed of small units and tiny teams of scholars, at least until the 1860s. A significant proportion of 12% of British chemists of the period still belonged to the social elite (landowners, lawyers, priests) against 9% in Germany and 6% in France, whereas 14% were physicians and 3% pharmacists[58]. Even the proportion of chemistry professors and lecturers, although slowly increasing, remained at a modest 34%, and only a small fraction of them were teaching at universities. In fact, quite a few positions for expert chemists had been established by professional corporations (of physicians, pharmacists, but also farmers), by scientific societies or societies for the improvement of agriculture and other useful arts. The number of chemists working for the State also increased because of the needs of the Mint, the production of powder and the various inspections of gas, food, water, drinks and chemicals. Except for the legal experts, a good num-

57 Golinski (1992).

58 Pharmacists still represented 16% of chemists in France and in Germany, physicians 4% of chemists in France and 3% in Germany (Sigrist forthcoming 1).

ber of these chemists were indeed performing routine analysis or expertise for local authorities on an independent basis. New industrial sectors, such as brewery and sugar refining, also took on chemists, so that manufactures employed 20% of chemists active between 1810 and 1860 in Britain against 10% in Germany and 9% in France. The mining sector mobilised an additional 3 to 4%.

The addition of all these positions, even though precarious in many cases, had an impact on the recruitment of chemists, so that by 1860 the size of the British community of chemists was close to the French one, except for the category of first rank chemists. In fact, no major research centre would emerge in Great Britain, so that the institutional landscape of chemistry remained a vast collection of small units different in orientation and purposes. The pattern of collaborations did not show in the 1830s the same radical changes that we have observed in Germany with the generalization of university laboratories. Nor did it show the continuous development of a national community of chemists on the model of France, where all the major researchers were concentrated in Paris. During the first half of the 19th century, British chemists still collaborated on a very casual basis (Fig. 8). And quite a substantial proportion of the recorded collaborations implied physicists, geologists, physiologists and technicians, a clear sign that scientific specialization was probably making slower progress in Great Britain than elsewhere.

The major groups of British chemists have already been identified on the previous graph of the most intensive and lasting collaborations (Fig. 7), notably the one based at the Royal Institution of London (Davy, Faraday, Brande) in the earlier part of the period. The inclusion into this group of lecturers such as John Bostock and Richards Phillips further shows the crucial importance for English chemistry of the major Londonian hospitals, especially Guy's, St. Barholomew's and St. Thomas's. After 1825-30, a series of new actors were able to develop collaborations with some disciples. One of them was Thomas Graham, himself a pupil of Thomas Hope, who first taught at the Andersonian Institution in Glasgow and later at the University College in London. Lyon Playfair, who moved between the Royal Institution in Manchester, the School of Mines and the Geological Survey in London, and the University of Edinburgh, developed collaborations with chemists and non-chemists alike. John Stenhouse, who first lectured at St. Bartholomew's in London before establishing himself as an independent chemist and moving later to the Royal Mint, also developed a few collaborations. The same is true for Robert Angus Smith, a former assistant of Playfair at the Royal Institution in Manchester, who made his career as general inspector for alkalis and for rivers in Manchester. Thomas Anderson, another well-connected chemist, was first employed in Edinburgh by the Agricultural Society of Scotland before becoming professor of chemistry at the University of Glasgow. Benjamin Brodie Jr, trained as a lawyer, was a kind of gentleman chemist who became in 1855 Aldrichian and Wayneflete professor of chemistry in Oxford. The already mentioned William Allen Miller made his career at the King's College of London and later at the Royal Mint, where he collaborated with some disci-

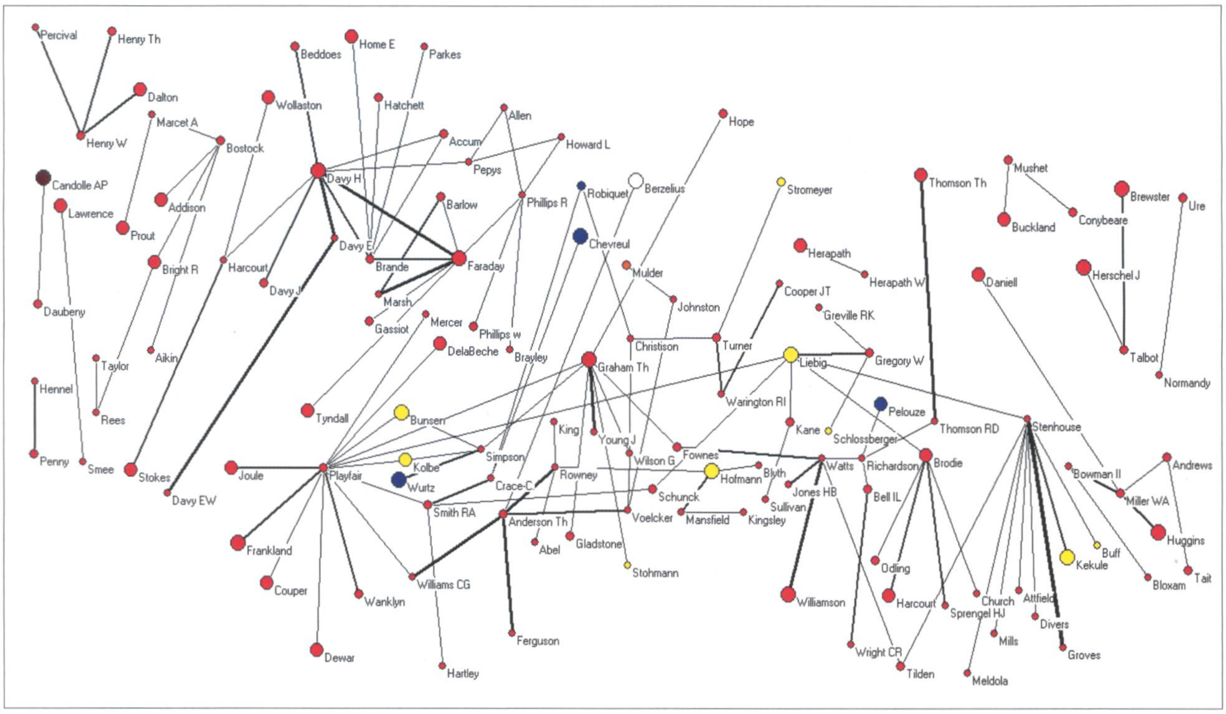

Fig. 8. Collaboration links between British chemists (A1 & B1) of the period 1810 to 1860.

ples. The same can be said of Henry Watts, when he worked at the University College in London before editing the *Journal of the Chemical Society*. All these biographical hints clearly show how diverse and scattered the institutional landscape of British chemistry remained in the first half of the 19th century.

A few remarks on the fourth period: the beginnings of modern chemistry (1860-1890)

Our statement about the increasing density of chemical networks in the period 1810 to 1860 is even more obviously valid for the next period, stretching from 1860 to 1890. Of course, a complete analysis of these networks would only be possible after a systematic inspection of the links with the chemists of the "Belle époque" between 1890 and 1914, a task which is beyond our reach for the moment. Nevertheless, a preliminary investigation, limited to more peripheral countries like Russia, the United States and the Austro-Hungarian Empire, already enables the recognition of a general trend towards more collaborations between chemists, in number as well as in intensity, even at the international level. The circulation of information and publications increased. The amount of translations as well, even though part of the phenomenon was due to the increasing number of languages used to publish chemical results: after Russian in the early 19th century, new chemical lexicons were developed after 1850 in Hungarian, Czech and Polish, allowing for the constitution, within the Habsburg Empire, of new national communities of specialists.

A superficial examination of the period 1860 to 1890 reinforces the statements already made for the previous periods about the increasingly technical training of chemists and about their growing professionalization, especially under the feature of the university professor. On the basis of a sample of 555 chemists of this period, 99 of them being of major importance, it appears that specialization and professionalization of training and research are largely connected to the impressive rise of agricultural, industrial and military chemistry. In Germany, where the perception of these stakes was the most advanced, 69 % of chemists of the period 1860 to 1890 followed a training at the "philosophy" faculties (*Philosophische Fakultäten*) or in the polytechnic schools (*Technische Hochschulen*)[59], whereas the basis for recruitment was enlarged by the introduction of chemistry in the programs of the *Gewerbeschulen* (professional schools) and the *Realschulen* (secondary schools). In Great Britain, 61 % of chemists had by then a high level of scientific training, partly performed at German Universities but also increasingly at home. In 1865, a doctorate in science was introduced at the University of London as an alternative to German Ph.Ds or to Scottish MDs[60].

In France, the proportion of superior scientific training was of 54 %, a proportion divided between the university faculties (31 %), the "Ecole Normale supérieure" or the "Ecole Centrale" (12 %) and the engineering schools such as Polytechnique or "Ecole des Mines" (11 %). Medical and pharmacy training still represented 18 % and 13 % respectively, even though the proportion of practicing physicians and pharmacists was much lower than that. Even in France, the German university system was by then considered as a model. Demands for institutional changes were partially satisfied in 1868 with the creation of the "Ecole pratique", which aimed at fostering practical training and doctoral research as well as recruiting high level university professors[61]. One of the four sections of the new institution was devoted to physics and chemistry under the joint direction of Wurtz, Balard and Jules Jamin. Four years after its creation, the "Ecole pratique" would already include 28 research laboratories, 20 of them hosted in Paris (at the Science and Medical faculties, as well as at the "Muséum"), plus 41 teaching laboratories (36 of them in Paris).

As a profession, the chemist was now a university or high school professor in half of the cases (i.e. 49 % of German chemists, 47 % of French and British chemists). He was sometimes teaching general chemistry but more often a specialized sub-field of chemistry, either mineral or organic, analytical or applied (to agriculture and to industry), physiological or pharmaceutical, and sometimes also special disciplines such as chemical engineering or toxicology.

As chemistry played an increasing role in industry, agriculture and military warfare, its practice was more and more perceived as a major agent of a nation's strength. After 1870, English, French and German observers agreed on the idea that chemistry had played a crucial role in the outcome of the Franco-Prussian war. On the industrial level, Great Britain seemed to keep the lead, since its industry employed 23 % of national chemists, a proportion superior to Germany (17 %) and to France (12 %). But this flattering proportion did not account for the fact that the German chemical community was much larger in size than those of France and Great Britain[62]. Furthermore, German universities did also work for national industries. The British manufacturers had therefore some

59 Only 8 % of German chemists of the period were trained in medicine and 13 % in pharmacy.

60 Training in arts was then limited to 10 % of British chemists, in medicine to 9 % and in pharmacy to 7 %.

61 Before that university professors were mainly recruited among secondary school teachers.

62 According to our estimations, the research potential of German chemistry (a notion which takes the importance of chemists into account) between 1860 and 1890 may have been superior by two thirds compared to Great Britain and by one third compared to France.

rights to express anxieties about their situation, and more precisely about the rise of the German dye industry. Their fears would receive confirmation in 1885 when Raphael Meldola, inventor of a blue synthetic dye used in textiles, paper and paints, had to abandon production because he could not cope with the intense competition made by German manufacturers. This failure sparked an intense debate on the causes of Britain's loss of its industrial production of dyes, a debate which would last until the World War I[63].

In this context of increased national rivalries, the French chemists put their hopes in a growing help from the State. At the time of the Franco-Prussian war, chemists working for the State already reached 14 % of the national community of specialists, compared to 8 % in Germany and 5 % in Great Britain. If the beating heart of German chemistry was in the university faculties and industries, the strongholds of French chemistry were in the high engineering schools ("grandes écoles") and in state-promoted laboratories. As for British chemists, they could rely on a dynamic industrial sector and on a multiplicity of institutions of all kinds. Despite the fears, voiced in each of these major countries, that national chemists and engineers were losing the competition, each nation could rely on specific advantages and followed its own way for developing its community of chemists.

On the other hand, chemists were now able to organize themselves at an international level, as it appeared in 1860 when the first international congress on chemical nomenclature was set up in Karlsruhe by August Kekulé, Adolphe Wurtz and Karl Weltzien. Beyond the institutional settings, which had a national character, and despite a certain variety of specialized research practices, the treatment of epistemic objects related to chemistry required a coordination of fundamental paradigmatic beliefs, a coordination that neither the exchanges of information nor the translations of existing literature could provide. Common decisions had to be made about the use of universal rules of nomenclature or about the adoption of standards such as the notion of atomic weight, which was proposed at the Karlsruhe conference by Stanislao Cannizzaro. From then on, the modern system of chemical investigations can be considered as fully established and operational[64]. This outcome was the result of continuous transformations which had happened since 1700, and the crossing over of the two threshold of the Chemical Revolution in the 1770s and the emergence of organic chemistry in the 1830s. Accepting common norms was the best way to ensure an improved coordination of investigations in the field of chemistry. It was a crucial step to stabilizing a scientific system which by then disposed of its own set of specific training and research institutions.

A concluding consideration method

Under the light of this empirical investigation, even limited to the networks of 18th and early 19th century chemistry, the coordination of scientific research and the development of modern science loose the simplicity they had in the classical theories of Kuhn and Polanyi. Comparing chemistry with botany, astronomy or even physics shows that there is no unified science, but an aggregate of scientific subfields with different characteristics and different levels of organization, coordinated by networks of variable shapes and density[65].

The coordination of scientific work was described long ago by Michael Polanyi in a classical article on the "Republic of Science"[66]. For Polanyi, the production of scientific knowledge was, and still is, organized in a way similar to the production of goods, operating as an aggregate of independent scientists "cooperating as members of a closely knit organization" and "freely making their own choice of problems and pursuing them in the light of their own personal judgment"[67]. Within this liberal system of coordination, each scientist has to adjust his efforts to fit in with the results achieved by all the others, taking into account the initiatives of the other scholars operating within the same system. The rules are the same for a particular discipline than for the global system. The image used by Polanyi to express his idea is that of a giant jigsaw puzzle made by a large number of participants, each of which has to continuously adapt his contribution to the evolving situation created by all the others. This conception implies a mechanism of self-adjustment, a kind of invisible hand similar to the self-regulating principles on which Adam Smith based his economic theory. More recent articles on the functionning of the Republic of Letters and Science did not attempt to account for any mechanism of regulation: they were happy to present scientific collaboration as guided by shared ideals about scholarly behavior.[68] Even Caroline Wagner's book on *The New Invisible College* opposes the free organization of international scientific networks to the state directed institutions of scientific research.[69] These publications testify in any case of the remarkable persistence of scholarly ideals about the collective elaboration of a universal knowledge which would be fully independent of any particular social context.

63 See the notice on « Meldola » in the *Oxford Dictionary of National Biography*.

64 On the notion of scientific system, see Rheinberger (1995).

65 For a comparison with the training networks of 18th century botanists, see Sigrist and Widmer (2011).

66 Polanyi (1962).

67 Polanyi (1962, p. 54).

68 Daston (1991a), Daston (1991b), Goldgar (1995).

69 Wagner (2008).

As shown in the present article, an empirical network approach has the advantage of considering the emergence of modern science as a dynamic process of coordination, which can be different from one disciplinary or national sub-system to the other. Direct interpersonal connections take the place of the invisible hand moved by individual enthusiasm or regulated by the objective rules of scientific production. Potential interferences in the system can be accounted for by the existence of dominant positions acquired by some groups or individuals, by the influence of some powerful institutions or major vested interests, and also by the unequal distribution of resources[70]. In the case of chemistry, the existence of clusters of specialists working in the same country or in the same city is a clear indicator that participation to the scientific enterprise is also shaped by goal-oriented institutions and State policies, if not dictated by economic and strategic considerations. The direct consequence of these collective constraints is the existence of a changing geography of scientific training and knowledge production. Among the shifts recorded in this article are the transfer of the major training schools from the early 18th century Dutch and Prussian medical centres (Leyden, Halle) to the French institutions of the Enlightenment and post-revolutionary periods (*Jardin du roi, grandes écoles*), and to the German universities after 1830. A network approach also documents the emergence of new scientific powers after 1830-1840, such as Russia, the United States and even the Habsburg Empire. Yet, how institutions, scientific policies, civil demands and economic interests influence knowledge production would be the matter for further monographic studies.

Another change of perspective produced by a network approach concerns the dynamics of the scientific development itself. Kuhn's seminal work on the structure of scientific revolutions[71] had presented scientific disciplines as built around paradigms shared by members of a given community of specialists. This included at least some common views about theory and practice of research in a given field, a set of values on how to validate contributions, and possibly also a common terminology to ensure a good circulation of information. In the case of chemistry, the "Pneumatic Revolution" of the 1770s and 1780s was supposed to have produced this first scientific paradigm, or perhaps a new paradigm if one accepts Stahl's phlogiston theory as being the first one. Nevertheless, in a *Kuhnian* perspective, a scientific revolution is little more than a transition between two stages of "normal science" based on different paradigms. The static aspect of this model does little justice to the continuous and dynamic developments of (Early) Modern science, to the various channels of transformation which are constantly at work and whose geography can be mapped by an empirical network approach. The case of Enlightenment chemistry also shows the coexistence of a literary and philosophical approach with various technical practices, the parallel developments of specialized and non-specialized approaches, as well as a strange mixture of amateurism and professionalisation. Early modern chemistry was made of a small academic nucleus governed by a paradigm (a true science) amidst vast informal fields of unsystematized knowledge of practical nature.

In fact, the poor quality of information about scientific connections makes it difficult to systematize any analysis into a coherent whole. Another limitation is caused by the uncertain frontier between a true chemist, working in an academic context, and other kind of actors able to produce and mobilize some sort of chemical knowledge. The poor presence of chemists within the networks of the 18th century Republic of Letters and Science may be the result of this uncertain status of the discipline. This means that other channels for transferring chemical knowledge must have existed, channels implying technicians, craftsmen or amateurs of various kinds. By considering the nature of 18th and early 19th century chemistry from the broader point of view of a comprehensive science of matter, Klein & Lefevre have indeed shown that hardly any ontological difference could be made between academic science and the practical knowledge provided by craftsmen, pharmacists, physicians, mining engineers and other men of practice[72]. This statement points to the need for further network studies and "prosopographies" which would include more categories of actors than the specialized chemists identified on the basis of our formal criteria. Yet, the limited specialization of the correspondence networks of chemists shows that the frontiers of the discipline remained blurred even after the triumph of Lavoisier's paradigm, and stayed so well into the 19th century.

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[70] At an individual level, fund-raising difficulties, personal ambitions and conflicts would also play a role.

[71] Kuhn (1962 / 1970).

[72] Klein & Lefevre (2007).

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