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PHYSICS, MATHEMATICS, AND CHEMISTRY IN AMERICA, 1870-1915
A COMPARATIVE INSTITUTIONAL ANALYSIS

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Social Science Working Paper
Number 139
August 1976

For publication in the proceedings of a symposium
on the development of knowledge in the
United States, 1870-1915

American Academy of Arts and Sciences
Newagen, Maine

June 1975

Not long before the nation's first centennial, the astronomer Simon Newcomb lamented that the United States stood embarrassingly behind the leading scientific countries of Europe in the practice of physics, mathematics, and chemistry.[1] Around 1870 the three disciplines were part of a prescribed undergraduate curriculum designed to produce not scientists or mathematicians but the generally cultivated man. Together, physics, mathematics, and chemistry accounted for less than one quarter of the typical undergraduate's studies. Allowed so little time in the curriculum, courses in these subjects rarely went much beyond the elementary level, and physics as well as chemistry, with a few institutional exceptions, was inculcated without laboratory instruction.[2] Students might pursue advanced work with the occasional research-minded professor. At Harvard there was the mathematician Benjamin Peirce, the chemist Wolcott Gibbs; at Yale, the physicist Arthur W. Wright, who held the first Ph.D. granted in the United States. But there were no good graduate schools in the country, certainly none offering high quality training in physics, mathematics, or chemistry. Students eager for advanced study in these fields usually went to Europe, especially Germany.

Whatever their training, physicists, chemists, and mathematicians had only limited employment opportunities. Chemists might set themselves up as independent consultants or actually find employment in business firms as analysts and assayists. But there was no significant industrial demand for practitioners in any of the three fields. In the burgeoning electrical industry, the type-case technological innovator of the day was of course Thomas Edison, the self-taught genius whose spectacular success was generally taken as proof that in business college training was not only unnecessary but a liability. Andrew Carnegie recalled that in the early 1870s chemistry was "almost an unknown agent in connection with the manufacture of pig iron." The blast furnace manager was usually "a rude bully, who was supposed to diagnose the condition of the furnace by instinct . . . ."[3] In ceramics, pulp and paper, or sugar refining, just as in iron and steel, there were hardly any chemists either. In the governmental sector, chemists were somewhat better off than mathematicians, for whom there were virtually no posts save in the Nautical Almanac or the Naval Observatory, or physicists, whose only significant place of federal employment was the U.S. Coast Survey. State geological surveys hired chemists; so did local gas commissions, assay offices, and the U.S. Department of Agriculture. But the vast majority of practicing physicists, chemists, and mathematicians were employed in the academic world, where they were largely occupied with teaching rather than with research.

About 32 chemists, 20 physicists, and probably still fewer mathematicians pursued and published research with any regularity.[4] Much of the research reflected the indigenous circumstances of the respective disciplines. More a servant than a queen of the sciences, mathematical investigations in America were mainly concerned with astronomical problems. Much of chemistry dealt with the analysis of minerals and waters and soils, or involved simple inorganic investigations, often of practical utility.[5] An important part of American physics was meteorology and geophysics. No small portion of European scientific work covered the same fields, but Europeans also explored the more "abstract branches of each discipline -- in mathematics, the emerging areas of analysis; in physics, heat, light, electricity, and magnetism; in chemistry, the structure and properties of inorganic and, especially, organic materials. In the abstract branches of mathematics, Americans could point to the accomplishments of Benjamin Peirce; in physics, of Joseph Henry; in chemistry, of Wolcott Gibbs. But the arena of abstract science and mathematics was dominated by Europeans.

In the United States, as in most European nations, neither physicists, mathematicians, nor chemists had a professional society devoted to their discipline. While members of all three disciplines participated in the affairs of the American Association for the Advancement of Science, where there were separate sections in each field, the AAAS did little for any branch of science between its annual meetings. The National Academy of Sciences was even more ineffectual. "The contrast between the eminent name of the Academy and the celebrity of its members on the one hand," Simon Newcomb, a member, noted, "and its means of doing either harm or good on the other, is ridiculous in a degree of which the members themselves can hardly help being conscious. It is too suggestive of eminent respectability out at the elbows."[6] From time to time, mathematicians and chemists had created special journals of their own; all had been short-lived. Chemists, physicists, and occasionally mathematicians published their work in the American Journal of Science or in local organs of equally broad disciplinary scope. Expressing their own accurate estimate of the quality and prestige of domestic journals, the practitioners in the three disciplines tended to send their best work abroad for publication.

Back in the late 1830s Joseph Henry had returned from Europe and announced to Alexander Dallas Bache: "the real working men . . . of science in this country should make common cause . . . to raise their own scientific character."[7] In the early 1870s, not least for reasons of cultural nationalism, the leaders of American physics, mathematics, and chemistry remained eager to improve the practice of their respective disciplines, to enlarge productivity in research, especially productivity in the abstract branches dominated by Europeans. Like their brethren in Europe, practitioners in all three disciplines were becoming more specialized, more ambitious to make their marks in professional scientific advancement rather than to contribute to the enlargement of general scientific culture. Reflecting the trend, in Des Moines, Iowa in 1874, Joel E. Hendricks, a self-trained mathematician, founded The Analyst, the first American journal regularly to publish original mathematical papers and the first in some time, perhaps the first ever, to be abstracted in the Jahrbuch über die Fortschritte der Mathematik. A few years before, 1870, Charles F. Chandler, professor of analytical chemistry at Columbia College, and his brother William H. Chandler, who was connected with a scientific school, established the American Chemist, an organ for the publication of abstract as well as practical research in that discipline. And in 1874, a group of chemists meeting at Northumberland, Pennsylvania to celebrate the 100th anniversary of Joseph Priestley's discovery of oxygen, were stimulated to call for the creation of a national chemical society. The move failed that year because of objections that the country was too large for a national society to be workable, and that no society so specialized could flourish. But in 1876, despite the objections, chemists in New York City led by William Chandler did create an American Chemical Society, with 53 resident and 80 non-resident members, which soon ambitiously began publishing the Journal of the American Chemical Society.[8]

The Chandlers hoped that the American Chemist would find support among industrial and commercial as well as among academic interests. Given the

prevailing attitudes of indifference if not hostility towards science in industrial circles, their hopes were doomed. In any case, the leaders of physics, mathematics, and chemistry in the United States tended to the posture expressed earlier by the chemist T. Sterry Hunt. While Hunt did not underrate the many practical benefits of chemistry, he believed: "Science for the millions is a humbug! True science, like true nobility, is essentially aristocratic."[9] It was in the post-Civil War decades that the phrase "abstract science" was replaced in the language of the scientific community by the phrase "pure science," which meant less purity of subject than purity of motive. Much of the scientific leadership of the day disdained the pursuit of science for profit, not least because profit makers had little use for them. To the leadership of American science, physics, mathematics, and chemistry were worth studying because they raised the cultural standing of the nation, ennobled and enriched the mind, encouraged well-disciplined habits of thinking.

Espousing these purposes, the scientific community may not have found much support among the industrial entrepreneurs of the day, but it did find enthusiastic patrons among a special group of Americans. College-educated, they were predominantly upper middle class, well-to-do professionals, businessmen of a mercantile cast, and landed gentry. Often described as "cultivated" Americans, they formed an enthusiastic audience for the post-Civil War popularization of science manifest in the lectures of a John Tyndall or Thomas Henry Huxley and in the vogue of the new Popular Science Monthly. Their interest in science was stimulated in part by the chief subjects of the popularizers, notably the theory of evolution, the mechanical theory of heat, the theory of the conservation of energy. All were intellectually exciting and accessible to the lay mind. No less important, their interest was strengthened by their affinity for the ideas of the scientific community, which they found especially appealing amid the business and political corruption of the era of Ulysses S. Grant.[10]

In the post-Civil War decade, a group of remarkably able new college presidents, all of them the products of cultivated homes, joined with their scientific faculties to reform the American system of higher education. Led notably by Charles William Eliot at Harvard, they assumed that by encouraging students to develop scientific habits of thinking, they would inculcate in them disinterested, noble habits of mind. Introducing the elective system in college studies, they encouraged the teaching of science by the laboratory method and established degrees in scientific subjects. To raise the nation's cultural standing, they also established graduate programs in scientific and non-scientific subjects. By the mid-1870s some 25 institutions awarded the Ph.D. in the United States, but the pace-setter in the movement for graduate training and research was the new Johns Hopkins University, which opened its doors in 1876 under the presidency of Daniel Coit Gilman.

Gilman's stellar faculty included, in mathematics James J. Sylvester, in chemistry Ira Remsen, in physics Henry Rowland. Sylvester, 62, a leading British mathematician who had never gained an appropriate academic post at home, was an eccentric enthusiast of his discipline with a special zeal for promoting research in the newer fields of abstract mathematics. Remsen, 29, a native American with a Ph.D. from Goettingen, was in contrast stiff and formal but also energetic, productive, and an ambitious advocate of organic chemistry . Rowland, a 27 year old product of Rennselaer Polytechnic Institute, had no graduate training, but he had taught himself Faraday, embarked on a program of independent research, and had already won the accolade of the great British physicist James Clerk Maxwell for his experimental work in electromagnetism.[11] Both Remsen and Rowland promptly established two of the finest research laboratories in the country for chemistry and physics. And all three professors gave thought to establishing journals to help promulgate the gospel of advanced research in their respective disciplines.

To Sylvester, The Analyst was no doubt an inadequate organ for his type of original mathematical research because the bulk of its articles dealt with applied topics. Not long after he joined the Hopkins faculty, Sylvester queried American mathematicians whether they would support a new journal. All but one of the forty respondents voted for the venture, though some did express the hope that the subject matter would not be so erudite as to intimidate American readers. In 1878, subsidized by the Hopkins trustees, Sylvester inaugurated the American Journal of Mathematics. Meanwhile Remsen, who had embarked on a prolific program of research in organic chemistry, found himself with nowhere to publish. The American Chemist was failing and the Journal of the American Chemical Society appeared only intermittently. And when Remsen submitted a long article to the American Journal of Science,

the editor, James Dwight Dana, rejected it on grounds that it would overwhelm his periodical. Eager to have the work of his laboratory properly recognized and also granted its due priority, Remsen prevailed upon Gilman and the Hopkins trustees in 1878 to sponsor a new Notes from the Chemical Laboratory, which in 1879 became the American Chemical Journal. In physics, Rowland did not try until 1884, and then unsuccessfully, to establish his own journal, perhaps because the output of the Hopkins laboratory was initially not that great. He failed in 1884 because Dana pleaded with Gilman not to permit the venture. Dana's American Journal of Science had already to do without chemistry. If it lost physics, the bulk of its pages would be devoted to geology, and Dana was sure that a purely geological journal could not command a sufficient number of subscribers to pay for itself.[12]

Led by Hopkins, in the 30 years following the outbreak of the Civil War, American universities produced 23 Ph.D.'s in mathematics, 33 in physics, and 41 in chemistry.[13] During this period, first-degree graduates and Ph.D.'s in chemistry especially found expanding employment opportunities in the public sector, notably at the local level where the public health movement created a rising demand for water and soil analysts, milk inspectors, and control technicians for the manufacture and sale of kerosene. At the state level, chemists also found posts in the growing number of agricultural experiment stations, which were authorized in every state and made financial wards of the federal government by the Hatch Act of 1887. At the federal level, the Department of Agriculture hired more chemists from the 1880s, while at least some new posts became available for chemists and physicists, too, in the new U.S. Geological Survey and the U.S. Weather Service. In industry, some chemists found jobs in drug firms, coal and oil distilleries, cottonseed oil plants, metal smelting enterprises, and gas works; a number continued to strike out successfully as independent entrepreneurs or consultants.

But the number of governmental positions for physicists, chemists, and mathematicians remained comparatively small, and there was hardly any industrial demand to speak of for Ph.D.'s in the three fields. In chemistry, industrial firms wanted analysts mainly, not organic chemists. Insurance companies needed only actuarial calculators, not mathematicians. And in 1884 the trade journal Electrical World succinctly expressed the attitude of its constituency: "Edison's mathematics would hardly qualify him for admission to a single college or university . . . , but we would rather have his opinion on electrical questions than [that] of most physicists." [14] In the post-Civil War decades, Ph.D.'s in physics, mathematics, and chemistry tended overwhelmingly to make their careers in the academic world.

There, professors of physics, chemistry, and mathematics increased the output of research in their respective disciplines. Between 1870 and 1893, 217 American physicists published 815 articles in European and American journals; 82 mathematicians, 272 articles; 327 chemists, 1186 articles.[15] At home, the large majority of chemical research found its way into Remsen's American Chemical Journal; of mathematical research, into Sylvester's American Journal of Mathematics. Physicists continued for the most part to rely upon the American Journal of Science, though the Harvard faculty published part of its work in the Proceedings of the American Academy of Arts and Sciences. More important than the enlargement in the output of research during this period was the increase in the number of practitioners in each discipline who were producing work of significance. Along with Remsen in chemistry, there was Frank W. Clarke, H.B. Hill, C.L. Jackson, A.R. Leeds, A. Michael, E.F. Smith, and J.H. Stebbins. In addition to Rowland in physics, there was Albert A. Michelson, A.M. Mayer, Carl Barus, and of course Josiah Willard Gibbs, a genius for any age. Even after Sylvester returned to England in 1884, in mathematics there was T. Craig, W.W. Johnson, Simon Newcomb, O. Stone, and W.E. Story. But despite the rise in quantity and quality of American physical, chemical, and mathematical research, at the opening of the 1890s, the practitioners of all three disciplines in America still felt themselves -- and probably actually remained -- less accomplished than their counterparts in the leading scientific nations of Europe.

The productivity of American physicists lagged behind that of Europeans. So evidently did that of American mathematicians and probably that of American chemists. A full 30% of the articles in Sylvester's journal was published by foreigners, but that was the result of a deliberate editorial policy to acquaint American mathematicians with the work of Europeans. More significant, a disproportionately large fraction of the articles by productive American authors in both Sylvester's journal and Remsen's American Chemical Journal were contributed by Johns Hopkins faculty or graduates.[16] Outside the Hopkins orbit in late nineteenth century academia, the encouragement of

graduate training and research was more honored in rhetoric than in reality. A growing fraction of the faculty, its ambitions fired by the model of the German university, might hunger for recognition in the world research community, but academic administrators were more concerned with their scientific faculty's pedagogical accomplishments. "Our aim," president Francis Amasa Walker of MIT put it, "should be: the mind of the student, not scientific discovery, not professional accomplishment."[17]

No less important, university presidents tended to discourage research on grounds that it would lead to narrow specialization, to the fracture of a general culture which they liked to believe could and should be preserved. If the late nineteenth century university was thus something of an arena of conflict between teaching and research, it was in a deeper sense a battleground between ideals of purpose -- between the diffusion as against the advancement of knowledge, between the education of widely literate citizens as against the training of professionals, between the preservation of a general culture as against the encouragement of specialization to a degree that would make general culture impossible.

In this conflict, the late nineteenth century university president held the more powerful hand. Lord Bryce observed that he exercised virtually autocratic powers; he controlled salaries, appointments, promotions -- in short, the entire system of academic rewards and incentives.[18] And the president used his powers to stress teaching over research in the use of faculty time, university resources, and even the design of laboratories. Of course the professors complained that they had too little time and support for research, but the professors of the day lived in a buyers, not a sellers, market. Unable to brandish offers from other universities, they had no leverage with which to force their own presidential superiors to modify policies, either for them as individuals or for their departments. If American physicists, chemists, and mathematicians were less productive than their European counterparts, it was because their academic circumstances and incentives simply discouraged the pursuit of research.

Outside the academic world, research of course remained unheard of in industry, and in federal agencies it was always in a precarious position, especially if it was the kind of research vulnerable to charges of impracticality. "We are not fomenting science," the director of the Coast and Geodetic Survey typically had to assure a Congressional investigating committee. "We are doing practical work for practical purposes."[19] At state agricultural experiment stations, chemists faced the difficulty of doing any research at all amid the demands of their agrarian constituencies. The soil scientist E.W. Hilgard complained of the California State Experiment Station in 1886: "There is no rest here for anyone, wicked or otherwise, least of all for a man who, like myself, is in a position which authorizes everyone from the shock-haired and hayseed-bestrewn granger to the justices of the supreme court to ply me with questions on their private business."[20] Nevertheless, like Frank W. Clarke, W.O. Atwater, or Harvey Wiley; like Simon Newcomb or Charles Saunders Peirce; like Carl Barus or Thomas C. Mendenhall, some of the more productive chemists, mathematicians, and physicists were employed in federal agencies and agricultural experiment stations.[21] Government chemists produced enough research to help make viable the new Journal of Analytical and Applied Chemistry, which was founded in the 1880s as a private venture by Edward Hart, one of the first chemistry fellows at John Hopkins.

If most governmentally sponsored research was understandably of a practical type, so was some academic work. But critics then and later who accounted for the inferior standing of American science by singling out its applied tendencies, implicitly idealized the situation abroad. In chemistry, European practitioners also paid considerable attention to applied subjects. In mathematics, while the percentage of articles published abroad in the field of abstract analysis was increasingly rapidly, some 30% of world research output dealt with such applied subjects as geodesy or physical theory or astronomy.[22] In any case, applied work could lead to fundamental results. The American mathematical astronomer G.W. Hill hit upon the idea of infinite determinants in the course of analyzing the relative motions of the three bodies: earth, sun, and moon. Josiah Willard Gibbs earned a place in the mathematical history books for his work on quaternions, during which he invented the modern notation of vector analysis and to which he had come via the route of electromagnetic theory. Agricultural experiment station scientists contributed to fundamental knowledge of, among other things, plant chemistry, and in physics Edison of course stumbled upon the Edison effect. More important, whatever the attention to applied research, a large part of the work published by Americans in mathematics and chemistry, and virtually all of it in physics, was in "pure," or fundamental, subjects.[23]

The trouble with physics, mathematics, and chemistry in late nineteenth century America was not so much in the subject matter as in the quality of the research, particularly in the kind of research likely to win accolades and reputations among the abstract scientific community of Europe. One is at hazard in attempting to specify what constitutes quality in science no less than in literature or art, but certain general features of merit do suggest themselves. Whether in theoretical or experimental science, quality frequently consists in explorations that throw light on a general category of phenomena or in the development of techniques that permit practitioners to deal with a wide variety of problems. In late nineteenth century chemistry, one would set high on the scale of quality the structural theory of the benezene ring and low on it the analysis of the constituents of an arbitrary organic compound. Similarly in mathematics, the more general -- and rigorous -- the proof, the more widely applicable the analytic technique, the higher the quality. On the scale of quality, the Pythagorean theorem of course stands far higher than the mere calculation of the sides of a particular right triangle. Late nineteenth century American mathematics seems to have consisted too much of mere calculations. American physics and chemistry in the same period lacked much of a theoretical side and too much of the experimental work consisted of mere fact-gathering as opposed to the gathering of significant facts or the invention of significant experimental techniques.

In part, the emphasis on fact-gathering revealed the degree to which American science derived from the idea that science proceeds merely by the accumulation of empirical data. Yet if this naive reading of Baconian instruction was strong in the United States, it was vigorous in Britain, too, and the British produced more high quality science without, it seems, having significantly more physicists, chemists, or mathematicians. More important than the American version of Baconism was the democratic assumption that lay implicitly beneath it -- since all data were of equal importance, so by extension were all data gatherers. But as the Nobel laureate Luis Alvarez once said, "There is no democracy in physics. You can't say that some second rate guy's opinion should count as much as [Enrico] Fermi's."[24] Even in late nineteenth century American physics, 85% of the research articles were published by 21% of the practitioners; in mathematics, 75% by 35%; in chemistry, 69% by 21%.[25] And within this productive group, a still smaller group -- the disciplinary elite -- produced the important work. The fundamental difficulty in American physics, mathematics, and chemistry of the day was that this disciplinary elite operated in an institutional framework that was more democratic in initiative than elitist in control, a system that offered the practitioners of the first rank little opportunity to set high quality standards for the research of the much larger second-rank group.

Standards of significance could have been set in first-rate centers of research and training, where concentrated members of the disciplinary elite might have stimulated each other and instilled in students a taste for the significant type of research. Apart from Johns Hopkins, the university system's commitment to graduate training was, like its commitment to research, generally weak. A physics student recalled that he went to Princeton for graduate work, "browsed in the library, played in the laboratory, and deteriorated intellectually." Felix Klein, the great German mathematician, whose institute in Göttingen was a magnet for advanced students everywhere, declared the preparation of Americans -- presumably he included those who came with college degrees -- for his higher courses "entirely inadequate."[26] The low quality of American graduate schools drove students in physics and chemistry as well as those in mathematics to study abroad, not only for doctoral but for post-doctoral training. For the three disciplines, the productive group in physics was twice as likely as the less productive to have studied in Europe; in mathematics, almost three times as likely; in chemistry, almost four times.[27]

At home, the majority of Ph.D.'s in each discipline were trained at a handful of schools. In physics, the schools were Hopkins, Harvard, and Yale; in mathematics, Hopkins and Yale; in chemistry, Hopkins, Harvard, Yale, and Columbia.[28] Yet save for Hopkins in mathematics and Harvard in chemistry, none of these schools had a concentration of any fraction of the respective disciplinary elites. The best organic chemist in the United States was Arthur Michael, but he was on the faculty at Tufts, which had no graduate program. Other chemists of merit, including E.F. Smith at the University of Pennsylvania and C.F. Mabery at Case Institute of Technology, taught no graduate students either. The physicist Albert A. Michelson was also at Case, and his highly capable colleague A.M. Mayer was at the Stevens Institute in Hoboken. In mathematics, G.W. Hill spent most of his

professional life at the Nautical Almanac in Washington, D.C. before retiring to his birthplace in upstate New York.

More generally, the productive, as opposed to the elite, group in physics was scattered through some 25 academic institutions; in mathematics, through 14; in chemistry, through 29.[29] In short, in late nineteenth century physics, mathematics, and chemistry, the small disciplinary elite and the larger productive groups were generally situated outside of the graduate training network. True, in physics there was a slight concentration of the productive, as distinct from the elite, group at Harvard, but most of its members there were like John Trowbridge, whose research fell squarely in the fact-gathering tradition. The only outstanding physicist at Yale was Willard Gibbs, who had only a handful of students throughout his career. Hopkins' sole source of strength in physics was Rowland, who did train a generation of able spectroscopists. And Hopkins, which had an able staff gathered by Sylvester and which graduated fully 43% of the mathematics Ph.D.'s published between 1878 and 1890, served students in that discipline exceptionally well.[30]

In chemistry, the productive practitioners at Yale and Columbia fell in the analytic or fact-gathering school. Harvard students might receive capable training in inorganic and even organic chemistry from Wolcott Gibbs, H.B. Hill, and Charles Loring Jackson. But here, too, Hopkins commanded the field, graduating a full 36% of the chemistry Ph.D.'s, or as large a fraction as Harvard, Yale, and Columbia combined.[31] In chemistry as in physics at Hopkins, the department was really little more than one man deep; the majority of students took their Ph.D.'s under Ira Remsen. Yet for all of Remsen's energetic evangelism for organic chemistry, his own research was largely in the fact-gathering tradition, which in organic chemistry meant the fabrication of new compounds and the analysis of their constitution. Of course, organic chemistry was in a stage when the accumulation of new compounds served a certain useful purpose, much the same as did Rowland's accumulation of more accurate spectroscopic data. Nevertheless, Remsen tended to encourage too much the doing of descriptive chemistry and too little the pondering of the more fundamental problems of chemical structure.[32]

Graduate schools aside, standards of quality could have been set by the journals in the respective disciplines. Physicists, remaining without one of their own in this period, continued to publish in Dana's American Journal of Science, but Dana, eager to maintain the disciplinary diversity of his journal so as to maintain a financially viable list of subscribers, was evidently willing to publish even mediocre studies by established physicists. In mathematics, The Analyst, and its successor after 1883, the Annals of Mathematics, continued to devote its pages largely to applied work; it was not a salient forum of merit for research in the newer abstract areas of the discipline. In contrast, the American Journal of Mathematics, with its high percentage of foreign authors and high editorial standards, seems to have done an excellent job both in introducing American mathematicians to key problems in abstract mathematics and in displaying models of what constituted high quality work. While in chemistry Remsen's American Chemical Journal ably promulgated the gospel of organic chemistry, it also tended to hold up Remsen's fact-gathering style of research as the model of meritorious effort in the field.

The glamour attached to Remsen's organic chemistry annoyed many inorganic chemists, including Frank W. Clarke, who in 1878 chided his American colleagues for making their "chief aim to discover immense numbers of new compounds, and to theorize upon their constitutions . . . . These chemists have devoted nine-tenths of their energy to the compounds of a single element, carbon." To Clarke's mind, there were three really great problems in chemistry which warranted considerably more attention than they were receiving. "First, what laws govern the transformations of energy that occur during chemical changes? Second, how do the properties of compounds stand related to those of the elements contained in them? Third, what is the nature of the chemical union?"[33] Clarke's critique of organic chemists in America was unfair; most were only following part of the program underway in Europe. But he was right to call his colleagues to account for paying so little attention to the emerging field of physical chemistry, which occupied little space in Remsen's journal, the chief organ for the publication of American chemical research. Virtually no one respected the Journal of the American Chemical Society, which, along with intermittent publication, was by common acknowledgement a forum for the weakest work. In the late nineteenth century, the productive group of American chemists published 16% of its work abroad; of American mathematicians, 19%; of physicists 21%.[34] And in all three disciplines these articles tended to include the

best work.

Apart from journals, standards of quality could also have been set by professional societies. But physics and mathematics remained without a professional society, and the American Chemical Society was hardly worthy of its name. While officers of the Society were slightly more likely than members of the productive group in their discipline to hold Ph.D.'s, and almost as likely to have studied abroad, their productivity rate was 25% lower than that of the productive group, and only 57% belonged to the productive group itself. No less important, 22% of their employment was in business or industry.[35] In short, the leadership of the Society was by most measures less involved in research than were the productive members of their discipline. Then, too, for a dozen years after its founding in 1876, all the directors of the Society were residents of New York City and vicinity. Chemists elsewhere, quite accurately perceiving the Society as more local than national in character, resented its claim to represent all of American chemistry. In 1881 the nonresident membership reached a peak of 124, then fell off by 1889 to 76. Even the resident New York membership, after rising to an 1884 peak of 119, fell off to 91. Some of the nation's best chemists had never joined the Society; many of those who did, including Frank Clarke, Ira Remsen, and William H. Chandler, resigned. In 1884, adding to the Society's difficulties, dissidents in the capital formed the Chemical Society of Washington, which was largely dominated by government chemists and doubtless connected with analytical rather than with organic subjects.[36]

Of course, members of all three disciplines could still rely upon the American Association for the Advancement of Science and the National Academy of Sciences. But the AAAS continued without a regular journal or much activity between its annual meetings. Besides, to the dissatisfaction of some scientists, the AAAS made no distinction between average and excellent practitioners of any discipline. Advocates of an elite scientific organization which might set standards of excellence in research looked to the National Academy of Sciences, yet the Academy published no regular journal either, held poorly attended and infrequent meetings, and had only a limited endowment income to parcel out for research. Then, too, since over half its membership came from federal scientific agencies, the Academy endured the same geographical resentments from non-Washington scientists

scientists as did the American Chemical Society from chemists outside of New York City.[37]

By 1890, physics, mathematics, and chemistry in the United States were unquestionably more capable than in 1870. Neophytes in each field could obtain first degrees in their subject and a nominal graduate training that often prepared them for work in the important areas of organic chemistry, abstract mathematics, and spectroscopic physics. The graduate pilgrimage to Europe had increased their contact with these important areas of research and also helped sensitize them more than they might have been otherwise to what constituted quality work in their disciplines. So to an extent had the new journals at home, especially in mathematics. And the emergence of universities and the enlargement of governmental science had provided not only rhetorical but in some cases real institutional possibilities for the pursuit of research. But while a solid foundation had been laid for the practice of the three disciplines in America, their rise to first rank awaited more of a concentration of means and able men in institutions devoted to research and training, publication, and professional activities. It awaited, in short, the accommodation of the elitism inherent in high quality science to the democratic assumptions and geographical pluralism characteristic of science in the United States.

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Yet by 1890, economic and technological forces were changing the status and opportunities of physics, mathematics, and chemistry in America. The electrical industry was beginning to shift from direct to alternating current. Posing more complicated technical challenges than direct current, alternating current rapidly moved the design of electrical circuits, machinery, and appliances beyond the capacity of the self-trained technician. About the same time, chemically-related industries such as iron and steel, fertilizer and sugar were finding it increasingly advantageous to employ analytic chemists. But more important, manufacturers in the newer areas of drugs and petroleum products, and especially coal tar dyes, increasingly felt a need for chemists in organic fields. By the early twentieth century, William McMurtrie, president of the American Chemical Society, happily observed: "We cannot yet boast with the Germans that single works employ

more than 100 thoroughly educated chemists . . . , yet many of the more important works have corps of chemists numbering from 10 to 50, while very many more have smaller numbers."[38]

While many of the chemists were at first put to such routine work as the improvement of the production process, a growing number eventually addressed themselves to product development, or applied research. And in the first decade of the twentieth century, a few firms in the more technologically intensive sectors of the electrical and chemical industries -- notably DuPont, AT&T, Westinghouse, General Electric, and Standard Oil of Indiana -- opened genuine research laboratories. The assumption behind the innovation was that new knowledge was likely to lead to new technology and ultimately to new markets and profits. The assumption paid off handsomely for General Electric, when Irving Langmuir's investigations of phenomena in the neighborhood of a hot filament yielded the nitrogen-filled lamp. In the chemical industry, research, as professor Marston T. Bogert of Columbia University noted, helped make pretty much a truth of the "old joke about the Chicago packing-houses using every part of the pig, including the squeal . . . . In modern abattoirs and packing-houses, the hides are used for leather; the grease is converted into soap, candles, oleo and glycerin; the blood and scrap into blood albumen, fertilizers, and potassium cyanide; the horns and hoofs into jelly, buttons, knife handles, etc; the feet, bones, and heads, into glue, bone oil and bone-black."[39]

The economic advantages of research in the physical sciences were recognized in the federal government when at the turn of the century, responding to a coalition of scientists and manufacturers, the Congress enacted a law creating the National Bureau of Standards. Established to determine standards not only of weight and length but of electrical and chemical quantities, the Bureau was authorized to conduct research in all pertinent areas of the physical sciences. All the while, spurred ahead by the assumption that chemical research would benefit agriculture, the chemical agencies in the Agriculture Department expanded in budgets and personnel. Similarly, the Adams Act of 1906 authorized original investigation at state experimental stations and supplied funds for the purpose. But at the same time, scientists like Harvey Wiley in the Agriculture Department's Bureau of Chemistry were joining forces with social reformers to prompt the passage of laws protecting Americans from adulterated products. After the

Pure Food and Drug Act of 1906, Wiley's Bureau of Chemistry was given additional duties in the regulatory sphere. Soon, too, the National Bureau of Standards enlarged its range of activities by embarking on a crusade for honesty in weights and measures. By 1915, the combination of economic development and regulation for reform had substantially increased the number of places for physicists and especially chemists in governmental agencies.[40]

Responding to the rising industrial and governmental demand, an increasing number of young Americans went to college to study science and engineering. Once introduced to high level courses in physics, mathematics, and chemistry, many remained in school to take doctorates. In the decade after 1895, physics became a field of rich intellectual excitement as a result of the discoveries of X rays, radioactivity, and the electron, not to mention the theories of special relativity and quanta. The advent of the electron also added luster to chemistry by rendering more answerable the questions Frank Clarke had posed about the dynamics of chemical bonding and transformations. Mathematics was proceeding at a rapid pace in the fields of topology, groups, abstract algebra, and function theory, and in 1900 the great German mathematician David Hilbert set out his celebrated list of twenty-three research problems which would prove difficult enough to occupy more than one mathematical generation. Between 1890 and 1915, American universities granted about 200 doctorates in mathematics, 300 in physics, and 500 in chemistry -- about ten times as many in each discipline as they had awarded in the previous quarter century.[41]

The more American scientists and mathematicians went into advanced work in electrons, organic structure, or mathematical groups, the more specialized they tended to become. Not only did chemists speak less to physicists and members of the two disciplines hardly at all to mathematicians; the disciplines themselves became increasingly fragmented. Expressing the trend, early in the century workers in two different branches of chemistry founded the Journal of Physical Chemistry and the Journal of Biological Chemistry. Worse, to some lay critics, whatever the discipline, science was rapidly leaving the realm of general culture. In 1906 the Nation complained: "Today, science has withdrawn into realms that are hardly [intelligible] . . . . Physics has outgrown the old formulas of gravity, magnetism, and pressure; has discarded the molecule and atom for the ion, and may in its recent generalizations be followed only by an expert in

the higher, not to say the transcendental, mathematics . . . . In short, one may say that the average cultivated man has given up science, but that science has deserted him."[42]

But there was hardly any stopping the trend to specialization, not so long as science remained an open, internationally competitive enterprise. Either scientists specialized or they failed to keep pace with the advances in their respective fields. In each discipline, the subject matter was growing increasingly complicated, beyond the accessibility of mere common sense expositions. Then, too, academic studies offered in each tended increasingly to be not so much education as professional training, even at the undergraduate level. And the elective system made specialization all the more likely in an academic environment which encouraged higher education to be commonly understood as preparation for a career. Besides, in industry and government, as in the respective professions at large, the demand was for specialists, no matter what the cultural cost.

In the context of the day, the specialists themselves celebrated less the ennobling, cultural values of science and more its utilitarian benefits. Rapidly disappearing was the disparagement of money-making typical of a Rowland or Simon Newcomb. The chemists, for whom the industrial and governmental demand was considerably greater than for physicists and mathematicians, led the way towards the utilitarian rationale. As early as 1892 Albert B. Prescott, the retiring president of the American Association for the Advancement of Science, told his fellow chemical practitioners: "The advancement of chemical science is not confined to discovery, not to education, nor to economic use. All of those interests it should embrace. To disparage one of them is injurious to the others. Indeed they ought to have equal support."[43] In 1909, eager to please its industrial constituency, the American Chemical Society established the Journal of Industrial and Engineering Chemistry.

Despite the new opportunities in utilitarian science, probably the bulk of Ph.D.'s in chemistry, and certainly the vast majority of them in physics and mathematics, made their careers in the academic rather than in the industrial or governmental sectors of research. If there was no industrial or governmental demand to speak of for mathematicians, in both areas electrical engineers were much preferred to Ph.D.'s in physics. McMurtrie estimated that 80% of the working chemists in the country were connected with industry, but he might have added not likely 80% of the Ph.D.'s. While the industrial trend might be towards hiring trained chemists, the experience of Otto Eisenschiml, the product of a Vienna technical institute, was not atypical. When Eisenschiml joined an American industrial firm, he found that he was the only employee among 12 with any training in chemistry and he was told by the chief of his laboratory, a former water pail carrier who had worked his way up, that there was to be "no university nonsense around here."[44] Of course, attitudes towards highly trained chemists or physicists varied from one sector of the industry to another. But even at the new research laboratory of Western Electric, only a small fraction of the staff was given the liberty to pursue its fancy in research. The bulk of employees did applied work, much of it of a routine nature. Scientists in government laboratories remained under the watchful eye of Congressionally attentive administrators, who were wary of permitting their staffs to explore subjects too remote from evident practical purposes.

In the academic world, in contrast, the argument that basic scientific research served both economic development and social reform was rapidly taking hold, and presidents in the leading public and private universities were transforming their rhetorical genuflections to research into the reality of budgetary and administrative commitments. The prevailing arguments aside, with the influx of undergraduates in courses to prepare for careers in science and engineering, the demand for professors of physics, chemistry, and mathematics climbed to an unprecedented height. Endowed with considerable bargaining power by the market demand for them, professors in the three fields joined with their colleagues in other disciplines to wrest from the president's office concessions affecting their professional lives. They won greater control over appointments, salaries, and promotions, and they used their new power to stress accomplishment in research as an important criterion in the assessment of academic merit.[45]

The increased incentives for research combined with the growth of practitioners in each discipline to produce a remarkable expansion of research output. Compared to the earlier period, in the quarter century after 1890 over three times as many physicists, 649, published research; over four times as many mathematicians, 338; and almost seven times as many chemists, 2218. Similar though considerably less spectacular was the enlargement of the productive groups, which in each discipline just about

doubled, reaching 83 as compared to 45 in physics; 71 as compared to 29 in mathematics; 154 as compared to 68 in chemistry.[46] In chemistry, the productive group was no doubt substantially larger still, since much of its research output was masked by industrial secrecy, a practice deplored by governmental and academic chemists alike. In any case, in the open literature about 13% of the physicists published 53% of the articles in their field; about 7% of the chemists, 46% in theirs; about 21% of the mathematicians, 69% in their own.[47] In each field, too, not only did the productive group increase in size but so did the disciplinary elite. The physics community included P.W. Bridgman, Karl T. Compton, William Duane, Robert A. Millikan, Robert W. Wood, and Richard Tolman. The mathematicians included H. Bateman, G.D. Birkhoff, G.A. Bliss, Maxime Bôcher, L.E. Dickson, G.A. Miller, E.H. Moore, Oswald Veblen, E. B. Van Vleck, and O. Wilcynski. The chemists included Marston T. Bogert, Moses Gomberg, C.L. Jackson, T.B. Johnson, E.P. Kohler, Irving Langmuir, Arthur Michael, Arthur A. Noyes, Theodore W. Richards, Julius Stieglitz, and H.L. Wheeler.

There was no institutional concentration of the disciplinary elite except in mathematics at the University of Chicago. There E.H. Moore built a remarkable department with O. Bolza and H. Maschke. G.A. Bliss assessed the enterprise: "Moore was brilliant and aggressive in his scholarship, Bolza rapid and thorough, and Maschke more brilliant but sagacious and without doubt one of the most delightful lecturers on geometry of all times. These three supplemented one another perfectly, and they promptly obtained for the Department of Mathematics at the University of Chicago a place among the recognized leaders."[48] Yet if there was no other concentration of any disciplinary elite, in the three fields a number of departments acquired depth with three or more staff members over the period among the productive groups. In physics, the departments included Harvard, Cornell, Michigan, Chicago, Illinois, Princeton, Wisconsin, Ohio State, and Minnesota, which together had some 36% of the employment positions in the field. In chemistry, the departments were Yale, MIT, Cornell, Harvard, Columbia, Chicago, Berkeley, Bryn Mawr, Illinois, Michigan, and Wisconsin, which together accounted for [illegible]6% of the employment positions. In mathematics, the departments were Chicago, Harvard, Princeton, Columbia, Hopkins, Illinois, Cornell, Pennsylvania, and Yale, whose combined employment positions accounted for 49% of the total.[49]

The more prominently productive departments drew a large fraction of graduate students. In chemistry, 72% of Ph.D.'s publishing in the period took their doctorates at 7 schools, 5 of which had productive staff in some depth. In physics, 71% earned their doctorates at 7 schools, 5 of which were staffed in productive depth. In mathematics, 86% took their doctorates at 8 schools, 7 of which enjoyed productive depth; Chicago alone, with its stellar department, accounted for 24% of the doctorates in mathematics.[50] After the turn of the century, there was a steady decline in the number of Americans who went abroad for doctoral study. Between 1898 and 1915, Americans earned 38 physics Ph.D.'s in European universities, compared to 44 from 1852 to 1897. In mathematics they earned 21, compared to 29; in chemistry, only 32, compared to 116. It could be said of all three fields as an American Subcommittee of the International Commission on the Teaching of Mathematics declared of its own: "The increase in the number of strong men in mathematics is resulting in added strength in an increasing number of institutions . . . . In those universities in which within the past ten years three more doctorates have been awarded, there is a degree of uniformity in the requirements which probably indicates and established a standard for the United States . . . . "[51]

All the while, the practitioners of the three disciplines had been further equipping themselves institutionally. In 1888 the young mathematician Thomas S. Fiske returned to New York City from studying in England where he had been stimulated by the meetings of the London Mathematical Society. Eager to develop a stronger feeling of comradeship in mathematics at home, Fiske and two other recent graduates of Columbia, all of them 23 years old, initiated the formation of the New York Mathematical Society. By 1894 the Society, now publishing a Bulletin which reviewed advances in the field, had a membership of 225 people and was renamed the American Mathematical Society.[52] Five years later, in 1899, professor Arthur Gordon Webster of Clark University, invited his colleagues elsewhere to join in the formation of an American Physical Society, and the inaugural meeting of the organization was held at Columbia in the spring. Meanwhile, activists in the Washington Chemical Society, notably Harvey W. Wiley and Frank W. Clarke, had grown increasingly eager for a genuinely national society in their discipline. New York chemists, eager to preserve the existing American Chemical Society, agreed to revise the charter so that residence in New York was no longer

required for any fraction of the officers. In 1891 the Society was reconstituted as a truly national organization.[53]

The American Chemical Society was made workable as a national organization by the device of establishing local sections, and by giving each section the right to elect one councilor for every 100 of its members. By 1901 the American Chemical Society had 13 local sections, all of them active; at least six held monthly meetings. The membership of the national society was close to 2,000 and its finances were in sound condition. In a similar vein, the American Mathematical Society established a local section in Chicago in 1896, another one in San Francisco in 1902, a third in the southwestern United States in 1906.[54] While the American Physical Society formed no local sections before World War I, it arranged to hold meetings, often three or four times a year, in different cities around the northeastern and midwestern United States.

The accommodation of local interests aside, each of the societies was centrally governed by a popularly elected council. But it was the council which nominated candidates for office, including the office of the council itself, selected administrative committees, and guided the society's professional activities. More republican than directly democratic, this system of governance made likely the selection of officers and councilors from the better qualified practitioners in the respective disciplines. While in each of the societies, the average productivity rate of the officers tended to be lower than the average of the entire productive group, it was far higher than the average productivity of all producers in the discipline. In the American Chemical Society, about 50% of the officers came from the productive group; in the Physical Society, about 56%; in the Mathematical Society, about 60%. In the Mathematical Society, the distribution of employment among the officers tended to match the distribution in the publishing members of discipline at large. But in the Physical Society, there was a disproportionately large representation of government physicists; in the Chemical Society, of chemists in business and industry. The societies themselves, in short, expressed and advanced the degree to which the respective disciplines were becoming not only abstract and academic but involved in the utilitarian institutions of the day.[55]

When the American Chemical Society was reformed in the 1890's, president Harvey Wiley acted to revitalize its Journal by inviting Edward

Hart to become the editor. Hart's own Journal of Analytic Chemistry was merged with the Journal of the American Chemical Society, which soon began appearing on a regular basis, in healthy competition with the American Chemical Journal. About the same time, 1893, professor Edward L. Nichols of Cornell founded The Physical Review, which was subsidized by the university's trustees. And at the end of the 1890s, officers of the American Mathematical Society proposed to Johns Hopkins a change in control of the American Journal of Mathematics. The reformers, sure that the Journal gave too much space to foreigners and too little to the competent work of Americans, wanted the periodical managed by editors representing the Society who would have all papers submitted promptly refereed by competent specialists. The university refused to go along. Undeterred, at a meeting in New York City the reformers persuaded loyalists of the Journal that the Society could certainly publish the record of its own activities, including the papers presented at its own meetings. To this end, in 1900 the first issue appeared of the new Transactions of the American Mathematical Society.[56]

But the appearance of new journals, even journals sponsored by professional societies, of course did not necessarily make for high standards of publication. Even now, the Journal of the American Chemical Society had its critics. "If I were editing a Journal, not a Society journal," Edward Hart explained in 1899, "I should undoubtedly reject some of the articles we have published, but under the present condition, and especially with the local sections as centers of disaffection, I think it is wiser to publish them than to reject them and have a row . . . , especially while the Society is growing. We should accept and print everything of the least value, for, we must try to avoid disputes and disaffection in the Society in order to secure a larger membership, without which, and the money obtained from it, we can do nothing, and with which we can do everything that should be done." But in the meantime, the Journal's editorial policies remained on the weaker side.[57] In 1907, 225 papers were submitted; Hart published 171 straightaway, another 31 after revision. Only 23, or less than 10%, were rejected, a rather low rate for a journal of high quality. In The Physical Review, four out of five articles published before about 1910 concerned the old physics of the nineteenth century rather than the new physics of X rays, radioactivity, or electrons, not to mention relativity and quanta. More important, a disproportionately large fraction of articles

in the journal were published by Cornell graduates or faculty.[58]

Quite in contrast, the Transactions of the American Mathematical Society began and remained at a decidedly high level of quality. Guaranteed a healthy subvention by a consortium of universities in its first ten years, it did not have to cope with the financial problem that plagued Hart. Moreover, it was edited by E. H. Moore, Thomas Fiske, and E. W. Brown, and Moore was a far better mathematician than either Nichols or his coeditor Ernest Merritt was a physicist. Moore did most of the refereeing himself for the first three years, but all three editors, in the recollection of Brown, "wrestled with our younger contributors to try and get them to put their ideas into good form." After July 1902, Moore and his associates relied on seven cooperating editors, all of high standing in the American mathematical community. In 1908 Moore was succeeded as chief editor by Maxime Bôcher, who was in turn followed by L. E. Dickson. In all, the Transactions of the American Mathematical Society set an inspiringly high standard for the discipline of its day.[59]

Gradually, the Physical Review improved, too, becoming increasingly a forum for the new physics, especially the physics of electrons. And in 1913 the Review was shifted from the sponsorship of Cornell to that of the American Physical Society, which made it an instrument of the national community in the discipline and endowed it with standards as high as those of the discipline's best practitioners appointed to the editorial board. Perhaps the journals of chemistry improved in quality, too, as more practitioners entered the field, but in 1909 William A. Noyes expressed the traditional critique of his discipline: "it seems possible that if we directed our thoughts more toward fundamental problems instead of towards the accumulation of compounds and of facts which are little more than permutations of compounds and of facts already known, more real progress could be made." Even though a committee of distinguished American mathematicians declared that too much trivial work passed for an original contribution in American journals, on the eve of World War I mathematics was probably the best developed of the three disciplines practiced in the United States.[60]

But whatever their relative standings, each of the three disciplines was solidly established in the universities, while both physics and especially chemistry were rapidly making their way in industry and government. Each had an exponentially increasing number of practitioners who were supplied with the ambition, incentives, and means to produce research at a rapidly rising rate. And each had emerging within itself a disciplinary elite of effective size and in substantial control of an institutional framework -- the centers of graduate training and research, the national societies, the journals -- appropriate in the American context to force higher the standard of mathematical, physical, and chemical research.

FOOTNOTES

1. Simon Newcomb, "Exact Science in America," North American Review, 119 (1874), 290. Except for Daniel J. Kevles, The Physicists: The Rise of a Scientific Elite in Modern America (tentative title; Knopf, forthcoming, 1977), there exist no comprehensive studies of the three disciplines in the United States for the period covered by this paper. Edward H. Beardsley, The Rise of the American Chemistry Profession, 1850-1900 (University of Florida Monographs, Social Sciences, No. 23; Gainesville, Florida: University of Florida Press, 1964) is an able pioneering work which requires revision. The same must be said of David E. Smith's much older History of Mathematics in America before 1900 (The Carus Mathematical Monographs, No. 5; Chicago: Mathematical Association of America, 1934) and of Florian Cajori, The Teaching and History of Mathematics in the United States (Bureau of Education, Circular of Information, No. 3, 1890; Washington, D.C.: Government Printing Office, 1890). The arguments and interpretations advanced in this essay about chemistry and mathematics are therefore intended to be tentative and suggestive of further work. In the writing of this paper, I have benefited from the comments of my fellow participants in the American Academy symposium, and I am grateful to the staff of the Academy for their patience. I also want to thank Jeffrey Sturchio, who is writing his doctoral dissertation on American chemistry in this period, for his advice on sources; D. Stanley Tarbell and Ann Tracy Tarbell for making available to me their draft study of Ira Remsen; Roy MacLeod for his acute criticisms of the penultimate draft of this paper; and especially Carolyn Harding for her untiring and reliable aid in the gathering and analysis of the statistical data.

2. Stanley M. Guralnick, "Science and the American College, 1828-1860," (University of Pennsylvania, Ph.D., Education, History, 1969), passim. The Yale curriculum typically devoted 0.71 academic years out of 4 to science. Catalogue of Yale College, 1866-67.

[26a follows]

3. Quoted in Beardsley, Rise of the American Chemistry Profession, p. 62.

4. Robert Siegfried, "A Study of Chemical Research Publications from the United States before 1880," (University of Wisconsin, Ph.D., History, 1952), p. 99. The number of physicists is taken from publishers in the American Journal of Science who contributed at least five articles from 1870-72 onward. Thomas Fiske, "Mathematical Progress in America," Bulletin of the American Mathematical Society, 11 (1904/1905), 238.

5. G.D. Birkhoff, "Fifty Years of American Mathematical Research," Science, 88 (Nov. 18, 1938), 462; C.G. Caldwell, "The American Chemist," Journal of the American Chemical Society, 14 (1892), 331.

6. Newcomb, "Abstract Science in America, 1776-1876," North American Review, 121 (Jan. 1876), 104.

7. Henry to Bache, Aug. 9, 1838, quoted in Nathan Reingold, ed., Science in Nineteenth Century America: A Documentary History (New York: Quadrangle, 1964), p. 85.

8. Charles Albert Browne and Mary Elvira Weeks, A History of the American Chemical Society (Washington, D.C.: American Chemical Society, 1952), pp. 10-21.

9. Quoted in Margaret W. Rossiter, The Emergence of Agricultural Science: Justus Liebig and the Americans, 1840-1880 (New Haven: Yale University Press, 1975), p. 123.

10. Kevles, The Physicists, Chapter II.

11. Hughes Hawkins, Pioneer: A History of the Johns Hopkins University, 1874-1889 (Ithaca: Cornell University press, 1960), pp. 34-35, 57-58, 47-48; D. Stanley Tarbell and Ann Tracy Tarbell, "Remsen Revisited: The Influence of the Johns Hopkins School on the Development of Organic Chemistry in the United States," unpublished manuscript in possession of the authors, pp. 1-5; Daniel J. Kevles, "Henry Augustus Rowland," Dictionary of Scientific Biography, XII, 577-79.

12. Hawkins, Pioneer, pp. 74-76; Dana to Gilman, June 20, 1884, Dana Family Papers, Stirling Library, Yale University, New Haven, Connecticut.

13. Daniel J. Kevles and Carolyn Harding, "The Physics, Mathematics, and Chemistry Communities in America, 1870-1915: A Statistical Survey," Social Science Working Paper No. 136, California Institute of Technology, October 1976, Table 7 (to be published).

14. Electrical World, IV (September 20, 1884), 96.

15. Kevles and Harding, "The Physics, Mathematics, and Chemistry Communities," Tables 1 and 3.

16. Paul Forman, John Heilbron, and Spencer Weart, Personnel Funding, and Productivity in Physics circa 1900 (Historical Studies in the Physical Sciences, Vol V; Princeton University Press, 1975), pp. 123, 184, 188, 190; Fiske, "Mathematical Progress in America," P. 239. Of the 68 productive chemists published in Remsen's journal, the 6, or 9% associated with Hopkins contributed 18% of the articles. Of the 29 productive Mathematicians published in Sylvester's journal, the 11, or 38%, associated with Hopkins published 60% of the articles. Kevles and Harding, "The Physics, Mathematics, and Chemistry Communities," Table 1 and Appendices III, V.

17. Francis A. Walker to Alpheus Hyatt, Aug. 29, 1889, Alfred M. Mayer-Alfred G. Mayer-Alpheus Hyatt Papers, Rare Book Room, Princeton University Library, Princeton, New Jersey.

18. On Bryce, see George W. Pierson, Yale: College and University, 1871-1937 (2 vols.; New Haven: Yale University Press, 1952), I, 129.

19. Joint Commission to Consider the Present Organization of the Signal Service, Geological Survey, Coast and Geodetic Survey, and the Hydrographic Office of the Navy Department . . . , Testimony, March 16, 1886, 49th Cong., 1 Sess., Sen. Misc. Doc. 82 (Ser. 2345), p. 54.

20. Quoted in Charles Rosenberg, "Science, Technology, and Economic Growth: The Case of the Agricultural Experiment Station Scientist, 1875-1914," in George H. Daniels, ed., Nineteenth-Century American Science (Evanston: Northwestern University Press, 1972), p. 198.

21. The portion of employment positions, i.e., posts occupied for a reasonable time, in government agencies held by productive physicists was 20%; by productive mathematicians, 17%; by productive chemists, including those at experiment stations, 13%. Kevles and Harding, "The Physics, Mathematics, and Chemistry Communities," Table 11.

22. Florian Cajori, A History of Mathematics (2nd ed.; New York: Macmillan, 1919), pp. 278-79; Aaron J. Ihde, The Development of Modern Chemistry (New York: Harper and Row, 1964), pp. 258, 363-64.

23. Typically, the physics articles in the American Journal of Science in 1882-85 were mainly concerned with dynamical electricity, light, spectra, heat, geophysical subjects, and meterology.

24. Alvarez is quoted in Daniel S. Greenberg, The Politics of Pure Science (New York: New American Library, 1967), p. 43. There were about 70 physicists in British higher education in 1890. Russell Moseley, "The Growth of Physics and Its Emergence as a Profession in Britain, 1870-1939," (M. Sc., History and Social Studies of Science, University of Sussex, 1971).

25. Kevles and Harding, "The Physics, Mathematics, and Chemistry Communities," Table 1.

26. The Ph.D. student was Henry Crew, quoted in William F. Meggers, "Henry Crew," Biographical Memoirs of the National Academy of Sciences, 37 (1964), 36; Felix Klein, Lectures on Mathematics: The Evanston Colloquium (New York: American Mathematical Society, 1911), p. 97.

27. Kevles and Harding, "The Physics, Mathematics, and Chemistry Communities," Table 1.

28. Ibid., Table 7.

29. Ibid., Table 11.

30. Ibid., Table 7.

31. Ibid.

32. Tarbell and Tarbell, "Remsen Revisited," pp. 2, 9, 19-20.

33. Quoted in Siegfied, "A Study of Chemical Research Publications," p. 110-11.

34. Kevles and Harding, "The Physics, Mathematics, and Chemistry Communities," Table 1.

35. Ibid., Table 13.

36. Browne and Weeks, History of the American Chemical Society, p. 21-31.

37. Daniel J. Kevles, "On the Flaws of American Physics: A Social and Institutional Analysis," in Daniels, ed., Nineteenth-Century American Science, pp. 147-51.

38. William Haynes, American Chemical Industry: Background and Beginnings (6 vols.; New York: Van Nostrand, 1945-54), I, 245, 395-96; Beardsley, The Rise of the American Chemistry Profession, p. 65; McMurtie, "The Condition, Prospects, and Future Educational Demands of the Chemical Industries," Journal of the American Chemical Society, 23 (Feb. 1901), 79-80.

39. Marston T. Bogert, "The Function of Chemistry in the Conservation of Our Natural Resources," Journal of the American Chemical Society, 31 (1909), 139.

40. Rexmond G. Cochrane, Measures for Progress: A History of the National Bureau of Standards (Washington, D.C.: National Bureau of Standards, Department of Commerce, 1966), pp. 1-87; Oscar E. Anderson, Jr., The Health of a Nation: Harvey W. Wiley and the Fight for Pure Food (Chicago: University of Chicago Press, 1958), pp. 85, 103-5, 113-14; Rosenberg, "Science, Technology, and Economic Growth," pp. 200-204.

41. Kevles and Harding, "The Physics, Mathematics, and Chemistry Communities," Table 8.

42. "Exit the Amateur Scientist," The Nation, 83 (Aug. 23, 1906), 160.

43. Prescott, "The Immediate Work in Chemical Science," Journal of the American Chemical Society, 14 (1892), 200.

44. Quoted in Beardsley, The Rise of the American Chemistry Profession, p. 63.

45. Joseph Jastrow, "The Academic Career as Affected by Administration," Science, 23 (April 13, 1906), 567; James McKeen Cattell, University Control (New York: The Science Press, 1913), pp. 20, 24; Maurice Caullery, Universities and the Scientific Life in the United States, trans., James Haughton Wood and Emmet Russel (Cambridge, Mass., 1922), p. 52.

46. Kevles and Harding, "The Physics, Mathematics, and Chemistry Communities," Tables 2 and 4.

47. Ibid.

48. Quoted in Smith, A History of Mathematics in America, p. 142.

49. Kevles and Harding, "The Physics, Mathematics, and Chemistry Communities," Table 12.

50. Ibid., Table 8.

51. Ibid., Table 15; "Preparation for Research and the Doctor's Degree in Mathematics," Bulletin of the American Mathematical Society, XVII (March 1911), 305.

52. Raymond Clare Archibald, A Semicentennial History of the American Mathematical Society, 1888-1938 (New York: American Mathematical Society, 1938), p. 4.

53. Webster to Carl Barus, May 1, 1899, Carl Barus Papers, John Hay Library, Brown University, Providence, Rhode Island; Browne and Weeks, History of the American Chemical Society, pp. 32-33, 36-38, 52.

54. Browne and Weeks, p. 53; William McMurtrie, "The Condition, Prospects, and Future Educational Demands of the Chemical Industries," Journal of the American Chemical Society, 23 (Feb. 1901), 74; Archibald, A Semicentennial History, pp. 8-9.

55. Kevles and Harding, "The Physics, Mathematics, and Chemistry Communities," Table 13.

56. Archibald, A Semicentennial History, p. 58.

57. Hart to Edward W. Morley, Aug. 1, 1899, Edward W. Morley Papers, Library of Congress, Box 33.

58. Journal of the American Chemical Society, 30 (1908), 14-15; Kevles and Harding, "The Physics, Mathematics, and Chemistry Communities," Appendix II. The subject distribution of articles in the Physical Review is from an analysis by the author.

59. Archibald, A Semicentennial History, pp. 60-61, where Brown is quoted.

60. Noyes, "Molecular Rearrangements," Journal of the American Chemical Society, 31 (1909), 1368; International Commission on the Teaching of Mathematics, Committee XII, "Graduate Work in Mathematics in Universities and in Other Institutions of Like Grade in the United States," Bulletin of the American Mathematical Society, XVIII (Dec. 1911), 133.