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Mathematics in America: The First Hundred Years

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1. Introduction. The hundred years after 1776 were good years for mathematics. In France, there were Lagrange, Laplace, Cauchy; in Great Britain, Cayley, Hamilton, Sylvester; in Germany, Gauss, Riemann, Weierstrass. Of course we recognize these names at once. But a comparable list of American mathematicians from 1776 to 1876 might draw puzzled looks even from an American audience. The list would include Nathaniel Bowditch (1773-1838), best known as author of the *American Practical Navigator* (1802) but who also published a four-volume translation and commentary on Laplace's *Mécanique Céleste*;[1] Theodore W. Strong (1790-1869), who proved some theorems about circles in the early 1800's;[2] Robert Adrain (1775-1843), who published some work on least squares and on the normal law of error,[3] and a host of astronomers, geodesists, surveyors, almanac makers, teachers of mathematics—and one president, Thomas Jefferson, who helped design quite a good mathematics curriculum for the University of Virginia.

To be sure, Benjamin Peirce (1809-1880) of Harvard published a major work in pure mathematics, the *Linear Associative Algebra*, but though he distributed a hundred copies of it in 1870, it was not actually published, and recognized in Europe, until 1881. In fact, in the period before 1876, Peirce was better known for his work in physics, astronomy, and geodesy than for his algebra, and was not yet seen as a towering figure on the purely mathematical scene. J. Willard Gibbs (1839-1903), the American mathematical physicist, is recognized now as the father of vector analysis, but his lectures on vector analysis at Yale did not begin until 1881. In the first hundred years of the republic, then, no American was an outstanding leader in world mathematics.

This bleak situation was widely recognized at the time, both inside and outside the United States. In 1816, for instance, the French philosopher

Auguste Comte was told not to go to the United States because mathematics was not appreciated there; even Lagrange, had he gone there, could have found employment only as a surveyor, Comte was told.[4] In 1840, in a survey of American higher education undertaken for the Corporation of Brown University, the authors lamented, "We have now in the United States...a hundred and twenty colleges....All teach mathematics, but where are our mathematicians?"[5] In 1873, the English mathematician and historian of mathematics Isaac Todhunter observed of the United States that

> with their great population, their abundant wealth, their attention to education, their freedom from civil and religious disabilities, and their success in literature, we might expect the most conspicuous eminence in mathematics.

Nevertheless, he said,

> I maintain that, as against us, their utmost distinction almost vanishes.[6]

Yet somehow, despite these modest beginnings, by the 1890's American mathematics was alive and well. Indeed, it was growing at a furious rate. In a count of American items listed in the German review journal *Jahrbuch über die Fortschritte der Mathematik*, there are four items in 1868, 32 in 1875, 43 in 1877. The number of American articles in one field, algebra, reviewed in the *Jahrbuch* between 1890-1900, is double that for the preceding decade.[7] By the end of the nineteenth century, the work of Americans was known and respected throughout the mathematical world.

The situation I have just described raises the two main questions I shall discuss in this paper. First, why was American mathematics so weak from 1776 to 1876? Second, and much more important, how did what happened from 1776-1876 produce an American mathematics respectable by international standards by the end of the nineteenth century? We will see that the "weakness"—at least as measured by the paucity of great names—coexisted with the active building both of mathematics education and of a mathematical community which reached maturity in the 1890's.

Before we begin answering these questions, let us introduce a useful chronological framework for the period to be discussed. From the Revolution to about 1820, we will find comparatively little mathematical activity. From about 1820 to the 1850's, we will find an interest in improving mathematics education, and much work in applying mathematics to mapping the new continent and the waters off its coast. Finally, from the 1850's to the 1890's, we find a major commitment by an emerging industrial America to a strengthening of the sciences—a strengthening process in which mathematics fully participated.

We will begin by surveying the sciences in general in the nineteenth-century United States. But we will concentrate on what was most important to mathematics.

2. Science in nineteenth-century America. The nineteenth century in general was a great one in the history of science: the century of Faraday and Maxwell, of Helmholtz and Mendeleev, of Darwin and Pasteur. None of these giants of nineteenth-century science was an American. The conditions for scientific research in the United States were relatively poor, for reasons peculiar to American history. First, "knowledge for its own sake" was not much valued in nineteenth-century America, and this remains true throughout our hundred-year period. For instance, in 1832, one American, James Jackson, denied his physician son permission to spend several years studying science before setting up practice. He said:

> We are a business-doing people. We are new. We have, as it were, but just landed on these uncultivated shores; there is a vast deal to be done; and he who will not be doing, must be set down as a drone.[8]

The astronomer Simon Newcomb, as late as 1874, observed:

> However great the knowledge of the subject which may be expected in a professor, he is not for a moment expected to be an original investigator, and the labor of becoming such, so far as his professional position is concerned, is entirely gratuitous. He may thereby add to his reputation in the world, but will scarcely gain a dollar or a hearer at the university.[9]

Because of attitudes like those just described, scientists could often find neither financial support for research nor the time to do it. When physicist Joseph Henry taught at Albany Academy in the 1830's, he taught seven hours a day.[10] As late as the 1880's, twenty hours a week was a common teaching load for professors of mathematics even in major colleges and universities.[11]

Other characteristic American attitudes also worked against science. For instance, after the Revolution, the newly independent Americans at first prized their isolation from Europe—not the best way to be part of a world scientific community. Moreover, science was sometimes seen as anti-democratic; after all, science is done by an elite, not by the common man.[12] Finally, and most important, while a central government in Europe might support science, the United States government was not automatically, by analogy, the patron of science, for federal patronage raised the issue of states' rights. In fact, though the U.S. government did sponsor scientific work when there was an apparent national need to be met, the states' rights issue long served to block the founding of any permanent federal scientific institution in the United States.[13]

Even with these attitudes, however, American natural science from 1776 to 1876 was stronger than its mathematics. The U.S. may point with pride, for instance, to the botanical work of John Torrey and Asa Gray; the physics of Joseph Henry; the founding of the science of oceanography by Matthew Fontaine Maury; and to the existence of a flourishing community of researchers in fields like geology, natural history, astronomy, and meteorology.

The state of mathematics would, then, seem to have been exceptionally low, and we must investigate why whatever promoted the natural sciences in nineteenth-century America did not equally encourage mathematics.

There were, first, two widely shared philosophical attitudes in America in the first half of the nineteenth century which supported the doing of science, if not of mathematics: Natural Theology and the Baconian philosophy.[14] Natural Theology is the doctrine that we may demonstrate the glory of God by discovering the laws of nature; indeed, the existence of natural laws proves the existence of an intelligent creator—God. The doctrine of Natural Theology was part of the world-view of the Puritans, and greatly influenced the colleges of New England in the seventeenth and eighteenth centuries. The doctrine was shared by the Founding Fathers, as reflected in a phrase in the Declaration of Independence: "Nature and Nature's God." Natural Theology, with its religious connotations, was a popular motive for doing science in nineteenth-century America; unfortunately, however, looking for the glory of God in nature is more encouraging to the natural sciences than it is to research in mathematics.

The Baconian philosophy, based on the work of the seventeenth-century philosopher Sir Francis Bacon, stressed three things: first, the importance for science of collecting facts; second, a de-emphasis of, and indeed condemnation of, all-encompassing theories; and, third, the application of science for improving human life. This philosophy was especially congenial to nineteenth-century Americans, both inventors and explorers. In nineteenth-century America, the popularity of the Baconian spirit encouraged the collection of vast amounts of data, especially significant for astronomy and for the biology and geology of a not-yet-explored continent. Baconianism, however, was not especially hospitable to work in mathematics, nor, indeed, to theoretical science in general.

Both Natural Theology and Baconianism were attitudes toward science that the United States had inherited from England. And we should note that another factor discouraging mathematics in the United States was the great influence of English thought, an influence especially marked in the period before 1820. England in the eighteenth and early nineteenth centuries, though producing notable work in the sciences, was quite weak in mathematics. One reason was the English devotion to Newtonian methods—even to notation in the calculus!—methods which by 1800 had been superseded on the Continent by the work of Euler, Lagrange, and Laplace. Another, related reason for England's mathematical weakness was the complete lack of advanced mathematics teaching at English universities.[15] Thus England, which might have served as a source both of inspiration and of textbooks, provided little help to American mathematics.

Nevertheless, there were major forces encouraging American science which also promoted mathematics. A principal impetus for scientific research in nineteenth-century America was the desire to explore, understand,

and subdue the new land. Just as geologists and biologists were needed to learn about the vast continent and its inhabitants, so people knowing mathematics were needed for the exploration: especially to map the coastline and the interior, and to make the astronomical calculations necessary for accurate mapping. National pride contributed also; there was a strong desire not to be dependent on foreign maps and charts for American navigation, for instance,[16] and there was even a proposal made to run the prime meridian through Washington.

The way American needs could encourage mathematical work is illustrated by the career of the first post-revolutionary American mathematical figure, Nathaniel Bowditch of Salem, Massachusetts. Bowditch, a seaman, taught himself mathematics. His original motivation was to understand and improve navigation; one result was his *American Practical Navigator,* first published in 1802 and still being revised and reissued today. Bowditch's major work, however, was a translation and commentary on Laplace's *Mécanique Céleste*; the subject of celestial mechanics was one to which an interest in navigation led many nineteenth-century mathematicians. The commentary was far from trivial; the kind of work involved is illustrated by Bowditch's well-known statement:

> I never come across one of Laplace's "*Thus it plainly appears*" without feeling sure that I have hours of hard work before me to fill up the chasm and find out and show *how* it plainly appears.[17]

For the future of American mathematics, Bowditch's importance includes having engaged the young Benjamin Peirce to help him correct the proofs for the Laplace commentary, thus giving Peirce an introduction to European mathematical physics not then available in any American college.

As Bowditch's interests illustrate, then, the need for accurate maps and charts promoted research in the mathematics related to these tasks: thus error theory, planetary theory, and celestial mechanics benefited. And in these areas, mathematical research was motivated not just by the altruistic desire to fulfill the needs of the nation, but by government funds.

One government institution arising from the need for exploration was the United States Coast Survey. To head the survey, Jefferson—our most mathematical of presidents[18]—found Ferdinand Rudolf Hassler, a Swiss who had worked on the survey of the canton of Bern. Hassler insisted, as a man with European training would, on a sound scientific basis being laid for the work of the Survey.[19] His successors, first Alexander Dallas Bache (1806-1867), and then Benjamin Peirce, shared this strong scientific orientation. The value of science and mathematics for the Survey is clear when we list the Survey's main tasks: the accurate surveying and mapping of the Atlantic Coast and Gulf of Mexico; mapping the Gulf Stream and secondary streams; determining the magnetic force, the depth of the ocean, and the nature of marine life, at various places; and precisely determining longitudes by astronomical observation. The Survey, while doing these tasks, as a consequence performed others as well: it provided its mathematically inclined employees with jobs related to mathematics, with a community to belong to, and with encouragement for work in the mathematics related to geodesy and astronomy. Thus, though the Coast Survey provided no specific impetus for pure mathematical research, it helped build and support a group of professional, mathematically-oriented scientists for the United States.

Another important institution arising from the needs of the new nation was the Nautical Almanac. Founded in 1849, its first head was Navy Lieutenant Charles Henry Davis, both a veteran of the Coast Survey and a former student at Harvard. The major technical problem in compiling a nautical almanac is to determine planetary positions at specific times at pre-determined points.[20] For this, the Nautical Almanac needed good astronomical observations, so Davis set up its headquarters in Cambridge, Massachusetts, which had Harvard College, a good telescope, and Professor Benjamin Peirce. Whatever the Navy may have expected, the atmosphere at the Nautical Almanac office was not so much practical and military as it was academic. Astronomer Simon Newcomb recalled how his going to work at the Nautical Almanac was entering the "world of sweetness and light."[21] Besides Newcomb and Benjamin Peirce, notable American scientists who worked at the Nautical Almanac included philosopher Chauncey Wright; mathematical physicist George William Hill; astronomer Benjamin Apthorp Gould; future M.I.T. president J. D. Runkle; the woman astronomer from Nantucket, Maria Mitchell; and future Wesleyan president J. N. Van Vleck. In 1858, Runkle started a mathematical periodical out of the Nautical Almanac office; called the "Mathematical Monthly," it lasted three years. Thus the Nautical Almanac not only aided the growth of the American mathematical community, it provided that community, at least for a time, with an instrument of communication.

The military needs of the United States provided further occasions for the work of mathematicians, surveyors, and astronomers. For instance, in 1848 Major William H. Emory, a West Point graduate with training in astronomy, led the Mexican Boundary Survey after the U.S. took the southwest from Mexico in the Mexican war. During the Civil War, Superintendent Alexander Dallas Bache made Coast Survey results available to the armed forces of the United States; and accurate Coast Survey data of Virginia in fact played a major part in the capture of Port Royal in 1861 by Captain Samuel F. Du Pont.[22]

And, as the nineteenth century progressed, the applications of the mathematical sciences in America began to extend beyond the calculation of planetary positions and the surveying of the United States. The sciences in general appeared useful both for military purposes and for the growing industries of the United States. The Civil War, for instance, encouraged scientists to study explosives, ironclad ships, the telegraph, and medical statistics. In civilian life, industrialists, particularly those in railroads and textiles, saw a great need for technicians and technically trained managers.[23] Also, the needs of American agriculture for a scientific—and thus more successful—basis were apparent.

Technically trained people were few, however, except for West-Point-trained engineers and the veterans of various surveys. Obviously more scientifically trained civilians were needed, and the place to get them was the educational system. Industrialists and government alike began to provide money for the educational system to produce such technically trained people. (Here developments in the United States parallel those in European industrial nations, especially Germany.) And the improvement of scientific education in the nineteenth century was especially significant for mathematics, since of all the sciences in the nineteenth-century world, mathematics—because it had become so technical—depended most on the educational system to produce competent practitioners. Indeed, outside the educational system it is difficult to become aware that mathematics—as opposed to its applications—can be a career at all. Thus the American educational system was absolutely necessary in generating mathematicians.[23a]

The teaching of mathematics in nineteenth-century America can best be understood by looking at the history of American higher education, especially the trends in science teaching. Accordingly, we will return to the period 1780-1820 to trace that educational history.

3. American higher education and mathematics: to 1850. Most American colleges in the seventeenth and eighteenth centuries had been intended to train ministers; by the early nineteenth century, however, this was no longer their primary function. College education was a gentleman's education, to produce a community of the educated. The educational theory which shaped the early colleges held that there was a pre-existing amount of truth, and that "the primary function of education was to get as much as possible of this corpus of Christian truth into the heads of the undergraduates."[24] If the amount of knowledge is fixed, there is no incentive for research. Another part of prevailing educational theory was that education should provide "mental discipline" for the student. Both the idea of mental discipline and the idea of a fixed body of received knowledge justified the curriculum of these colleges: chiefly, the classics and mathematics; and also some logic, some moral philosophy, and some of what was called "natural philosophy"—physics and astronomy. The scientific part of the curriculum was more oriented toward natural theology than toward practical application; in fact there was really no technical education, save at West Point, much before the middle of the nineteenth century.

Choosing subjects which provided "mental discipline" did give mathematics a greater share of the curriculum than the other sciences. The level of the mathematics taught, however, was not very high, especially when

English influence abounded before 1820. The mathematics usually taught in the colleges was arithmetic, elementary algebra, and the geometry of Euclid, with bits and pieces of surveying, trigonometry, or conic sections thrown in. Even elementary subjects were not always well taught. For instance, an instructor at Dartmouth after the Revolution is supposed to have taught Euclid without proofs, telling his class, "If you doubt the truth of the theorems, read the proofs; but for [my] part [my] mind is satisfied."[25] Even for relatively advanced subjects, teaching was often by rote; in 1830, there was a student riot at Yale against the way mathematics was being taught, known as the "Conic Sections Revolt."[26] Few colleges before the Civil War taught even calculus; almost none required it; and when it was taught the justification might still be "mental discipline." And—most important—the mathematics that was taught was part of a prescribed course of study which left no room for a student to specialize.[27]

Two things were necessary to improve college mathematics teaching: first, departure from the eighteenth-century English model; this was accomplished in the 1820's as part of a general wave of educational reform; second, a new stress on modern science and on a scientific and mathematical curriculum which would meet the needs of a growing industrial society. This second development began at mid-century, but was not really completed until the 1890's. Let us now turn to these two changes.

The old colleges and the education they provided changed because of pressures from American society. The United States, so self-consciously democratic, could not retain the idea of a "gentleman's education" forever.[28] A more practical orientation seemed more relevant to the needs of the nation. And, as the number of colleges multiplied, there was competition between them for students, which encouraged innovation in curriculum. One available innovation was to offer a richer program in science and mathematics.

Both in the United States and in England, educational reformers brought French mathematics into college mathematics teaching in the early nineteenth century. In the United States, the development was encouraged by world affairs. In England after 1812, France was not popular, but in the United States after its War of 1812, it was England that was unpopular. French mathematics came into the United States through the textbooks used to teach mathematics and its applications at French military schools and at the *École polytechnique* in Paris. The *École polytechnique* had been founded during the French Revolution. Education at the *École polytechnique* was intended to produce a *polytechnicien,* one with enough scientific knowledge to be able to apply it to a wide range of problems, and therefore one who knew some mathematics.

In 1818, John Farrar, Professor at Harvard, began a project of translating French mathematics textbooks for American use. Unfortunately, the very latest French mathematics and physics of the 1820's, like that of Cauchy and Ampère, were not included in Farrar's program, but even the eighteenth-century works by men like Bezout, Biot, Lacroix, and Legendre on surveying, trigonometry, algebra, and calculus were a great improvement over what had been taught in the colleges. The French works were both more up to date and more useful for the sciences. Farrar's work at Harvard was not unique; other schools began to teach French mathematics, and other professors undertook translations, notably Elias Loomis at Yale and Charles Davies at West Point. The availability of these new textbooks helped spark a much stronger mathematics program in many colleges.[29]

Just as important as New England colleges like Harvard and Yale in the history of mathematics education in early nineteenth-century America was the work of Sylvanus P. Thayer in reorganizing the curriculum at West Point, on the model of the French military schools and the *École polytechnique.* Besides Thayer, West Point had on its faculty Claude Crozet, a graduate of the *École polytechnique,* and Charles Davies, whose translation of Legendre's introduction to geometry and trigonometry (known as Davies' *Legendre*) was one of the most widely used American mathematics textbooks of the nineteenth century. Because of Thayer, Crozet, and Davies, not only did West Point provide pre-Civil-War America with most of its mathematically trained surveyors and engineers—for instance, providing the Coast Survey with Superintendent Alexander Dallas Bache—but the influence of West Point's mathematical curriculum on American education after the 1830's was immense. The mathematics programs at many schools were developed by professors who were graduates of West Point, including the universities of South Carolina, Mississippi, and Virginia.[30]

By the 1840's, the colleges of the United States still did not provide a scientific education comparable to the best available in Europe. Nevertheless, many American college graduates now had respectable mathematical backgrounds. The colleges may not have produced mathematicians, but they did produce a generation of teachers of mathematics who could respond to the new demands made around 1850 on the American educational system.

4. Mathematics and science education: 1850-1900. By 1850, the railroads, canals, bridges, roads, telegraphs were becoming major factors in the American economy. European research in agricultural chemistry was attracting American attention. Most educated Americans agreed that science was needed to improve industry and agriculture. Furthermore, research, to enlarge the amount of useful scientific knowledge, was also needed. All these things—the growth of industry, the settlement of the continent, and the consciousness of the importance of science—coincided with the growth of great fortunes in nineteenth-century America. Thus private wealth was available to finance education on a scale never before seen in the United States.[31]

In 1847, Abbott Lawrence, the textile magnate, founded the Lawrence

Scientific School at Harvard, hoping to produce graduates able to take their places in modern industry. At about the same time, a scientific school was founded at Yale. In 1861, it was named after Joseph Sheffield, who had funded it with his railroad holdings. The model of European polytechnic institutes—Paris, Dresden, Freiburg—now influenced not only textbooks, but entire institutions; not only the scientific schools at Harvard and Yale, but also (among others) Rensselaer Polytechnic Institute, Brooklyn Polytechnic, and "Boston Tech," later renamed M.I.T.

The land-grant colleges, also, stressed instruction in the sciences. First chartered by the Morrill Act of 1862, the land-grant colleges, which were intended to teach scientific agriculture, eventually included universities like Michigan, Wisconsin, Minnesota, and Cornell, and the various Agricultural and Mechanical schools throughout the nation. The founding of all these schools meant that the sciences in general, and therefore mathematics in particular, were much more widely taught; and the curricula of the new schools influenced the older colleges too. Instruction was not always of the highest quality, since it was impossible to staff so many new schools at once with qualified teachers, and the science which was taught was sometimes narrowly vocational. Nevertheless, the scientific schools provided jobs for mathematicians and scientists, and also made possible a level of instruction that had not existed before.

In the 1850's at the Lawrence Scientific School, mathematics and physics were taught by Benjamin Peirce. Peirce himself had worked under Farrar at Harvard and had assisted Bowditch in preparing his commentary on Laplace, so Peirce's mathematical roots are in the French mathematics of the eighteenth century. But Peirce taught, not eighteenth-century French science, but nineteenth-century European science, including the mathematics and physics of Cauchy, Hamilton, Gauss, and Bessel—without doubt the most advanced mathematical curriculum ever yet seen in the United States. To a man, Peirce's students testify that his lectures, though inspiring, were impossible to follow. Nevertheless, he must have taught them something. His students included many of the most influential scientists and mathematicians of the next generation. For instance, when Cornell in the 1880's developed a mathematics program of international stature, three leading men—Wait, Byerly, and later Oliver—were former students of Peirce.[32] Other Peirce students include astronomers Simon Newcomb, Edward Ellery Hale, and George William Hill; future Harvard Presidents Eliot and Lowell; future M.I.T. president J. D. Runkle; to say nothing of Peirce's sons, Harvard mathematics Professor James Mills Peirce, and the renowned philosopher and logician Charles Sanders Peirce. To be sure, Benjamin Peirce's mathematical curriculum was not home grown; his advanced mathematics and physics were learned from European sources. But his early education, and the financial and institutional support for his work—first French mathematics and physics, then the Nautical Almanac, Coast Survey, and Lawrence Scientific School—were typical of the situation of mathematicians in the nineteenth-century United States. Benjamin Peirce's career illustrates also the way American mathematics gradually changed from the practical to the more theoretical. Though Peirce was best known in nineteenth-century America for his contributions to applied mathematics, he published, near the end of the century, the first major American contribution to pure mathematics, his *Linear Associative Algebra.* This work, influenced by Hamilton's treatment of quaternions, gave methods of classifying and exhibiting all the linear associative algebras with a given, finite number of fundamental units, making use of the concepts Peirce developed of nilpotent and idempotent elements.[33] And the first sentence of Peirce's work has ever since been quoted as a definition of pure mathematics: "Mathematics is the science that draws necessary conclusions."

A similar pattern may be found in the career of J. Willard Gibbs. His father had been a professor of philology at Yale, and Gibbs grew up in the academic community of New Haven. His education was based on the Yale versions of French mathematics and its applications, and his thesis was in engineering: "On the form of teeth of wheels in spur gearing." After receiving his Ph.D. from Yale in 1863, however, Gibbs went to Germany to pursue his scientific studies, and moved there from engineering to mathematics and physics. He returned to Yale to teach and to do research. But even at Yale, there was no support yet for a great research scientist—literally no support, because Gibbs' professorship carried no salary. Only when Johns Hopkins offered him a job in 1880 did the Yale Corporation arrange that "an annual salary be attached to the chair of mathematical physics."[34] These difficulties notwithstanding, though, advanced scientific training at Yale, as at Harvard, produced students able to teach advanced mathematics and science. Yale's most illustrious mathematics student in the late nineteenth century was future University of Chicago professor E. H. Moore. Moore was at Yale in Gibbs' time, but Moore's major professor at Yale was mathematician Hubert Anson Newton, himself a Yale graduate, and it was Newton who made possible Moore's further education in Germany.

Despite the illustrious careers of Peirce and Gibbs, however, not even the Lawrence and Sheffield schools were dedicated to scientific research. Even after the Civil War, specialized advanced study in the United States generally existed only for those preparing for professions, not for those wanting to pursue knowledge for its own sake.[35] As late as 1875, Charles Sanders Peirce complained that Harvard did not "believe in the possibility of any great advances in science ... being made there," thinking that "the highest thing it can be is a school."[36] But with the intensified American interest in science, this situation could not last long, because in Europe there was a model not only for scientific subject-matter, but a model for the research institution—the German university.

Establishing university education in the United States was almost inevitable by the 1870's. Science-educated students from many American schools, sometimes with European post-graduate study, were available to staff universities; industrial fortunes were available to pay for them; the German model was there to inspire them. A key date is the centennial year 1876, when the first research-oriented university in the United States was funded, from a characteristic source—the fortune in Baltimore and Ohio Railway stock of Johns Hopkins. Johns Hopkins' first president, Daniel Coit Gilman, himself had a science degree from Yale. In fact, the presidents of almost all the research-oriented universities of the late nineteenth century were trained as scientists: F. A. P. Barnard of Columbia, David Starr Jordan of Stanford, A. D. White of Cornell, G. Stanley Hall of Clark, and C. W. Eliot of Harvard.[37] Some universities, like Clark and Chicago, were newly founded in this period; others, like Harvard and Yale, grew out of existing colleges. But whatever the immediate origin of an American university, the sciences were decisive in its development.

The elective system, pioneered by Eliot at Harvard, was part of the new university. The elective system strengthened mathematics in two ways. First, students did not have to study mathematics unless they wanted to, so the way was open for professors to teach more demanding courses. Second, students could deepen their knowledge in a chosen field—mathematics, for instance—as much as they might desire.

Of all the schools I have mentioned, the most important for American mathematics in the 1870's was Johns Hopkins. Because the Test Acts in Britain were not repealed until 1871, the eminent English mathematician J. J. Sylvester, who professed the Jewish religion, was not eligible for a chair at Oxford or Cambridge for much of his career.[38] Since Sylvester was available after his retirement from the Royal Military Academy at Woolwich in 1870, President Gilman made him the first professor of mathematics at Johns Hopkins (not the only time American mathematics has profited from European religious restrictions). Sylvester built a research-oriented department at Hopkins between 1877 and 1883 (before he returned to England to take the Savilian chair at Oxford newly vacated by the death of H. J. S. Smith). Sylvester's Hopkins students went on to teach mathematics and do research all over the United States. Two of them, Fabian Franklin and Thomas Craig, remained at Hopkins; others introduced modern mathematical teaching to many leading American universities: for instance, George B. Halsted at the University of Texas; Washington Irving Stringham at the University of California at Berkeley; C. A. van Velzer at the University of Wisconsin.[39]

Sylvester was not just a teacher and researcher, but the nucleus of an American mathematical community. Accordingly, in cooperation with three Hopkins colleagues, William E. Story, Simon Newcomb, and physicist H. A. Rowland, and with Harvard professor Benjamin Peirce, Sylvester founded the *American Journal of Mathematics* in 1878. Unlike earlier and shorter-lived American journals, the *American Journal* was neither a repository of problems nor an instrument of education; its primary purpose was "the publication of original investigations."[40] Among the articles in the first number of the journal were contributions by American mathematicians at Hopkins, Cincinnati, Princeton, Pennsylvania, and Virginia; two papers from mathematicians in Canada; one from Lipschitz in Bonn; three from Cayley at Cambridge; two from W. K. Clifford in London. Among the first hundred subscribers to the new American journal are, of course, American colleges and the U.S. Coast Survey, but we also find on the list Charles Hermite; the University Library at Cambridge, England; and the library of the *École polytechnique* in Paris—a sort of coming full circle, given the influence of the *École polytechnique* on American mathematical education. American mathematics was clearly on the world map. But Sylvester could not possibly have put it there all by himself, as his unsuccessful stay some thirty-five years before at the University of Virginia shows. Sylvester certainly helped, but, more important, there was by 1880 an American mathematical community, centered at the leading colleges and universities as well as in government agencies.

The level to which American mathematics had reached in the 1880's has been preserved for us by a survey taken for the United States Bureau of Education by Florian Cajori, then Professor at Tulane. The chief mathematics instructional officers in each of 168 colleges and universities answered his questionnaire. Though among the schools not responding were Harvard and Yale, the survey nevertheless provides us with a valuable "stop-action" picture of the change taking place in the United States from the mathematical education of the nineteenth to that of the twentieth century.

Asked, "How many hours do you teach?" many report twenty hours a week, but answers on the order of "ten" appear also. Asked "What else, if anything, do you teach?" 73 of the 118 who answered report teaching subjects outside of mathematics as well as mathematics; of these 73, 32 report teaching outside the physical sciences altogether, including—in 1888!—art, music, bookkeeping, languages, classics, history, and Bible. But 45 of the 118 say they teach only mathematics.[41]

More important, both the quantity and quality of mathematics teaching was increasing. As for the quantity, 112 schools reported that mathematics was elective. When asked, "Is the percentage of students electing higher mathematics increasing?" only three of the 112 report that the percentage is decreasing, 28 say no change, five say "yes" with qualifications, and 76 say without qualification that the percentage is increasing.[42]

The increase in quality can be shown from the type of training now available even to those teachers of mathematics outside the universities, and by the encouragement to do research reported even by college faculty members. Thus, for example, professors at many colleges in 1888 report having studied for a time at institutions providing excellent mathematical education like Johns Hopkins, Harvard, or Yale; and T. H. Safford, Field professor of mathematics and astronomy at Williams College—another former Benjamin Peirce student—reported that his professorship required him "to advance astronomical knowledge."[43]

Finally, in response to the question "What mathematics journals are taken?" 117 of the schools—in 1888!—list *none*. Eleven schools take only the *American Journal*; twelve more take only the *Annals of Mathematics*, which had been founded in 1884 by Ormond Stone (1847-1933) at the University of Virginia. But 28 schools take a number of mathematics journals, including the major European ones.[44] These 28 schools include most major state universities in the midwest and south, the Naval Academy, and private institutions like Northwestern, Vanderbilt, Columbia, and Johns Hopkins.

Thus, though the mathematical standards of Hopkins, Harvard, Yale, and Columbia had not yet trickled down to all schools, the process was well under way. As late as 1904, it is true, 20% of the members of the American Mathematical Society report having studied abroad.[45] But this statistic, paradoxically, helps illustrate the strength of the new American mathematical community. The American university taught these students that European mathematics existed and what it was like; it taught them enough mathematics to benefit from the European training when they got it; and most important, it welcomed them back to use their European training to produce American Ph.D.'s ready to be members of the world mathematical community.

All these trends—economic, educational, and mathematical—came together in the founding by industrialist John D. Rockefeller of the University of Chicago in 1892. Under E. H. Moore, the mathematics department at Chicago became the source of the first generation of American-trained mathematicians of world stature, whose careers will be described in Professor Birkhoff's paper; they included L. E. Dickson, O. Veblen, G. A. Bliss, G. D. Birkhoff, and R. L. Moore. When in 1893 the International Congress of Mathematicians was held under the auspices of the new University at Chicago, invited papers were given not only by illustrious Europeans, but also by thirteen Americans. American mathematics had come of age and was now part of the international mathematical community.

In the 1890's, with the founding of the American Mathematical Society[46] in 1888, the *Bulletin* in 1891, the University of Chicago in 1892, the International Congress in 1893, Felix Klein's Evanston Colloquium of 1893, the *Transactions* in 1900, there was an explosion of mathematical activity in the United States. As we have seen, this explosion in American mathematics was not a creation out of nothing, not a sudden flowering out of previously barren soil. Its roots lie in the influx of French mathematics teaching in the 1820's; it was nurtured by government support for applied mathematics throughout the century, and by the increase in science education which began in the

1850's; and it came to fruition in the universities of the 1870's, 1880's, and 1890's. We may, then, proudly exhibit the institutions and the people that produced the flowering of mathematics in the United States at the end of the nineteenth century as the major achievement of American mathematics in its first hundred years.

Notes

1. On Bowditch, see D. J. Struik, Yankee Science in the Making, New York, 1962, chap. 3, *et passim*; Nathan Reingold, "Nathaniel Bowditch", Dictionary of Scientific Biography, Scribner's, New York, 1970, vol. II, pp. 368-9, with bibliography.

2. On Strong, see George Daniels, American Science in the Age of Jackson, New York and London, 1968, pp. 224-5; cf. H. Poincaré, "Introduction" in The Collected Mathematical Works of George William Hill, Washington, 1905, vol. I, pp. vii-viii, on Strong's influence on his most notable student, G. W. Hill.

3. On Adrain, see J. L. Coolidge, Robert Adrain and the beginnings of American mathematics, Amer. Math. Monthly, 33 (1926) 61-76.

4. Florian Cajori, The Teaching and History of Mathematics in the United States, Washington, 1890, p. 94. This book is a gold mine of all sorts of information.

5. Richard Hofstadter and C. De Witt Hardy, The Development and Scope of Higher Education in the United States, New York and London, 1952, pp. 24-5.

6. Cajori, *op. cit.*, p. 99.

7. D. E. Smith and Jekuthiel Ginsburg, A History of Mathematics in America before 1900, Chicago, 1934, 154-157.

8. Quoted by Donald Fleming, William H. Welch and the Rise of Modern Medicine, Boston, 1954, p. 8.

9. I. B. Cohen, Science in America: The Nineteenth Century, in A. M. Schlesinger, Jr., and Morton White, Paths of American Thought, Boston, 1963, pp. 167-189; Newcomb's statement is quoted on p. 185.

10. Nathan Reingold, ed., Science in Nineteenth-Century America: A Documentary History, London, Melbourne, Toronto, 1966, p. 71.

11. Cajori, *op. cit.*, pp. 345-9.

12. Nathan Reingold, American Indifference to Basic Research: A Reappraisal, in George Daniels, ed., Nineteenth-Century American Science: A Reappraisal, Evanston, Ill., 1972, pp. 38-62, see p. 60; cf. Struik, *op. cit.*, p. 239.

13. See A. H. Dupree, Science in the Federal Government, Cambridge, Mass., 1957, p. 5 *et passim*; F. Rudolph, The American College and University: A History, New York, 1962, records opposition on this basis even to the land-grant colleges, p. 250.

14. Daniels, American Science in the Age of Jackson, Chapters 3-5.

15. W. W. R. Ball, A History of the Study of Mathematics at Cambridge, Cambridge, 1889.

16. Struik, *op. cit.*, p. 412.

17. Cajori, *op. cit.*, p. 104 (italics in original).

18. D. E. Smith, Thomas Jefferson and mathematics, Scripta Math., 1 (1932-33) 3-14.

19. Dupree, *op. cit.*, pp. 53-55; Struik, *op. cit.*, pp. 406-7.

20. Simon Newcomb, The Reminiscences of an Astronomer, Cambridge, Mass., 1903, pp. 63-4.

21. Newcomb, *op. cit.*, Chapter 3.

22. Dupree, *op. cit.*, p. 133.

23. H. Miller, Dollars for Research: Science and its Patrons in Nineteenth-Century America, Seattle and London, 1970, p. 75; B. Sinclair, The Promise of the Future: Technical Education, pp. 249-72 in G. Daniels, ed., Nineteenth-Century American Science: A Reappraisal, p. 261; cf. Hofstadter-Hardy, *op. cit.*, p. 31.

23a. R. V. Bruce, A Statistical Profile of American Scientists, 1846-1876, pp. 63-94 in Daniels, Nineteenth-Century American Science, pp. 87-9, shows that, among American scientists in the mid-nineteenth century, mathematicians were 50% more likely than other scientists to have chosen their field because of their experiences at school. In career choices made by other scientists, family influences or possible jobs were more significant.

24. Hofstadter-Hardy, *op. cit.*, p. 14; cf. the Yale Report of 1828, summarized in Rudolph, *op. cit.*, pp. 130-5.

25. Cajori, *op. cit.*, p. 74.

26. Cajori, *op. cit.*, p. 153; Stanley Guralnick, Science and the Ante-Bellum American College, Philadelphia, 1975, p. 55.

27. Daniel Kevles, On the Flaws of American Physics: A Social and Institutional Analysis, pp. 133-151 in Daniels, Nineteenth-Century American Science, points out that this was also a factor discouraging the growth of American physics, p. 136.

28. Hofstadter-Hardy, *op. cit.*, p. 22; Rudolph, *op. cit.*, Chapters 6, 10.

29. Stanley Guralnick, *op. cit.*, chapter 3; L. G. Simons, The influence of French mathematics at the end of the eighteenth century upon the teaching of mathematics in American colleges, Isis., 15 (1931) 104-23.

30. Cajori, *op. cit.*, pp. 195, 209, 220, 248.

31. Hofstadter-Hardy, *op. cit.*, p. 31.

32. Cajori, *op. cit.*, p. 178.

33. Benjamin Peirce, Linear associative algebra, Amer. J. Math., 4 (1881) 97-215; addenda, pp. 216-229. For the place of this work in the history of algebra, a brief account may be consulted in E. T. Bell, The Development of Mathematics, New York, 1945, esp. p. 249. On Peirce, see first Carolyn Eisele, "Benjamin Peirce", Dictionary of Scientific Biography, vol. 10, pp. 478-81, with bibliography.

34. Reingold, *op. cit.*, pp. 318-19.

35. Hofstadter-Hardy, *op. cit.*, p. 61.

36. Reingold, *op. cit.*, p. 228.

37. Hofstadter-Hardy, *op. cit.*, p. 33.

38. For an account of the nine-year campaign in Parliament to repeal the Test Acts, as well as some examples of their effects at Oxford and Cambridge, see D. A. Winstanley, Later Victorian Cambridge, Cambridge, England, 1947, chapter 3. These laws were, to be sure, anachronisms in the society of late nineteenth-century Britain, and Sylvester was showered with honors from his countrymen, from being an FRS at age 25 to his presidency of the Mathematics and Physics section of the British Association for the Advancement of Science in 1869. Nevertheless, he officially could not even take his degree at Cambridge until 1871.

39. Cajori, *op. cit.*, p. 272. Stringham, by the way, had been an undergraduate at Harvard and studied under Benjamin Peirce. Halsted, before going to Texas, also taught for five years at Princeton.

40. Amer. J. Math., Pure and Applied, I, p. iii.

41. Cajori, *op. cit.*, pp. 345-9.

42. *Ibid.*, p. 303.

43. *Ibid.*, pp. 346-9; p. 347, 386.

44. *Ibid.*, p. 302.

45. D. E. Smith and J. Ginsburg, *op. cit.*, p. 112; the statistics come from T. S. Fiske's presidential address to the American Mathematical Society in 1904.

46. First called the New York Mathematical Society. For the history, see R. C. Archibald, A Semicentennial History of the American Mathematical Society, 1888-1938, in American Mathematical Society: Semicentennial Publications, vol. I, New York, 1938.