The Evolution of a Community of Mathematical Researchers in North America: 1636–1950[1]

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ABSTRACT

This paper explores the various factors which effected the emergence of communities of mathematical researchers in North America beginning in the last quarter of the nineteenth century and their development in the twentieth. The analysis for the United States will hinge on a periodization defined largely by broader political and social influences; contemporaneous developments in Canada will be highlighted.

1 The Seventeenth and Eighteenth Centuries: Mathematics in Colonial Settings

Although the colonial period in what eventually became the United States began with the landings of English ships and the establishment of colonies on the eastern coast of the continent in the first two decades of the seventeenth century, the story of mathematics in colonial North America may be said to begin in 1636 with the founding by Puritans of the Massachusetts Bay Colony of Harvard College as a Congregationalist institution.[2] In trying to account for the professionalization of mathematics in North America, it is not by chance that the first colleges in the British colonies south of what would become the border with Canada were Congregationalist, and this includes Harvard and Yale (as well as Dartmouth, Williams, Bowdoin, Middlebury and Amherst).[3] As heirs of "rational and hierarchical Calvinsim in America" [Baltzell 1979, 248], Congregationalists valued the intellect and a certain liberality in education, especially at Harvard where mathematics was taught beginning in 1638 in keeping with the English universities, especially Cambridge, on which it was modeled.

At the time Boston was small, with a population of around 7,000, and the number of students at Harvard at first numbered no more than a dozen at most. The college itself was poor and the 400£ legacy of John Harvard was spent mostly on buildings [Morison 1956, 38]. The people of New England, however, were so intent upon supporting Harvard that

1 This talk has drawn from the unpublished English versions of the following two chapter-length essays: Joseph W. Dauben and Karen Hunger Parshall, "Dal Liberal Arts College alla Research University: Harvard, Yale e Princeton [From the Liberal Arts College to the Research University: Harvard, Yale, and Princeton]," in *Matematica e Cultura*, ed. Claudio Bartocci and Piergiorgio Odifreddi, 4 vols. (Turin: Giulio Einaudi Editore S.p.a., 2007), 1: 477-504; and "L'evoluzione della ricerca universitaria: Johns Hopkins, Chicago e Berkeley [Mathematics and the Evolution of the Research University: Johns Hopkins, Chicago, and Berkeley]," in *Matematica e Cultura*, ed. Claudio Bartocci and Piergiorgio Odifreddi, 4 vols. (Turin: Giulio Einaudi Editore S.p.a., 2007),1: 505-529. Compare also [Parshall 2003].

2 The Collège de Québec was actually founded in Nouvelle-France one year earlier in 1635, but did not begin to teach a complete classical course until 1659. See below.

3 The Congregationalist movement, which dispensed with any organized administrative heirarchy and placed ultimate responsibility for the local church in the hands of its congregation, in England was greatly influenced by the writings of the theologian Robert Browne. In America, prominent Congregationalists in the colonial period included John Cotton and Jonathan Edwards.

in 1644 the New England Confederation[4] requested that every family in New England give a quarter bushel of wheat, a shilling in cash, or the equivalent "for the mayntenance of poore Schollers at the Colledg at Cambridg" [Morison 1956, 38-39].

Although Harvard trained students for the ministry, it was not a seminary (more than half its students followed secular pursuits upon graduation). All students took a prescribed course in six of the traditional Seven Arts, which included arithmetic, geometry, and astronomy; they also studied philosophy, Hebrew and Greek, as well as ancient history. It was assumed that its students knew Latin, which was the language of instruction and most of the textbooks, all of which closely paralleled the curriculum at the Old Cambridge. The professional study of theology began only upon completion of the bachelor's degree; what the College was meant to educate were "gentlemen" and to "advance *Learning* and perpetuate it to Posterity" [Morison 1956, 43].

Yale had similar educational goals, although it was founded in New Haven in 1701 in part as a reaction to dissatisfaction with what some viewed as the excessively liberal ecclesiastical views of members of the Harvard faculty. The ten Congregationalist ministers who established the new school were, in fact, all Harvard alumni. According to Yale's charter, its purpose was to constitute a collegiate school "wherein Youth may be instructed in the Arts and Sciences who through the blessing of Almighty God may be fitted for Publick employment both in Church and Civil State" [Kelley 1974, 7]. To the clergy who comprised Yale's early faculty, this seems to have meant primarily theology as the "basis, security, and test" of the arts and sciences, construed on narrowly Calvinist terms [Kelley 1974, 33].

Between them, Harvard and Yale exemplified the highest level of mathematical learning and education possible in colonial North America. Although Jesuit missionaries had founded the Collège de Québec in Nouvelle-France in 1635, one year before the founding of Harvard College, the Collège de Québec only began to offer a complete classical course of study—including mathematics—in 1659, and mathematics was taught there primarily as a subject secondary to natural philosophy.[5] Moreover, with the French defeat to the English in 1759, the Collège closed its doors permanently [Archibald and Charbonneau 2005, 142-147]. From that point until the union in 1840 of the French and English Canadas, French Canada was an English colony that had its own educational institutions, although these were still collèges or secondary schools in which mathematical education was geared primarily toward commercial mathematics [Archibald and Charbonneau 2005, 152]. A parallel situation obtained in English Canada.

At Harvard, meanwhile, Isaac Greenwood held a chair for mathematics established by Thomas Hollis, an Englishman, in 1727.[6] Greenwood announced a series of lectures advertised as the first course on science in New England that promised to impart to

4 The New England Confederation was founded in 1643 by several of the colonies of New England, most prominently those of Massachusetts Bay, Plymouth, Connecticut, and New Haven, for their mutual defense and protection, primarily from the native Indians. The Confederation lasted for about 40 years, until it disbanded in 1684 over political disagreements between its colonial members.

5 A professorship of hydrography, first established in 1671, was held by Martin Boutet who had also served as professor of mathematics at the Collège de Québec [Archibald and Charbonneau 2005, 143-144.]

6 This was the first chair of mathematics to be founded in what would become the United States. Unless otherwise noted, all of the material quoted here concerning the life and works of Isaac Greenwood is drawn from the account given in John Langdon Sibley's *Lives of the Harvard Graduates, College Classes, 1642-1773*, as reprinted in [Shipton 1963, 170-182].

subscribers “a competent skill in Natural Knowledge.” He expected to perform more than three hundred “curious and useful Experiments” with various instruments and machines and to acquaint listeners with “the wonderful Discoveries of the incomparable Sir Isaac Newton.” Soon thereafter, Greenwood was elected “Professor of Mathematicks & Natural & Experimental Philosophy,” and thus was “settled at last in the only position in America where a man could live by science.” This was not, as yet, a position exclusively for mathematics, but it was at least the first step.

Greenwood also wrote in 1729 the first American-produced book of arithmetic to be published in the colonies [Wagner 1950, 55] and was the first contributor to a fledgling tradition of science in New England.[7] Two of his papers were published in the *Philosophical Transactions of the Royal Society*, and his teaching left its mark, for among his pupils was John Winthrop, who later succeeded Greenwood as Harvard's Hollis Professor of Mathematics.[8]

Winthrop, after Benjamin Franklin, is often regarded as the greatest American-born contributor to science in the eighteenth century.[9] Born in Boston in 1714, he entered Harvard in 1727 and was officially installed as Hollis Professor in 1739. He immediately undertook a series of astronomical observations that were published in the Royal Society’s *Philosophical Transactions* (the first of eleven papers he eventually published there). This work ultimately earned him a fellowship in the Royal Society of London in 1766. Relative to mathematics, Winthrop taught the usual elementary subjects, but in 1751, he also introduced the much more advanced study of fluxions.

The first to leave his mark on mathematics at Yale was Thomas Clap, a Harvard graduate (class of 1722) and Congregationalist minister.[10] Clap built the first orrery in the colonies, was an advocate of the “new sciences,” and of Newtonianism in particular. As soon as he assumed his responsibilities at Yale, moreover, “Mathematical subjects leaped into prominence.” Beginning in 1743, freshmen studied arithmetic and algebra; sophomores geometry, and third-year students, algebraic conics and fluxions. In 1758, problems on fluxions began to appear in commencement examinations, and became increasingly difficult over subsequent years [Simons 1936, 217-10; Tucker 1971, 64]. Unfortunately, Clap was the only member of the staff at Yale who could teach the fluxional calculus, and when he left in 1766, the subject disappeared from the curriculum.

An important part of Clap’s legacy, however, was the cohort of students he taught in the sciences, who went on to serve on the faculty at other colonial colleges like Dartmouth. Nevertheless, Clap’s legacy was a limited one, for “First and foremost, Clap

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7 The first arithmetics would not appear in French Canada until eighty years later with the publication in 1809 of Jean-Antoine Bouthillier's *Traité d'arithmétique pour l'usage des écoles* [Archibald and Charbonneau 2005, 150-151].

8 Material here concerning the life and works of John Winthrop is drawn from the account given in John Langdon Sibley’s *Lives of the Harvard Graduates, College Classes, 1642-1773*, as reprinted in [Shipton 1963, 349-373].

9 The renowned French scientist Louis-Antoine de Bougainville, known for his work both in mathematics and in natural history, was stationed under Montcalm in Québec in 1756 and until the fall of Nouvelle-France to the English in 1760 [Archibald and Charbonneau 2005, 145].

10 In what follows, unless otherwise noted, all of the material quoted here concerning the life and works of Thomas Clap is drawn from the account given in Leonard Tucker’s study, “President Thomas Clap of Yale College: Another ‘Founding Father’ of American Science,” [Tucker 1962, pp. 55-77].

was a Puritan, and like all Puritans he refused to venture at length on the strange sea of thought." Moreover, it has been said that Yale's preoccupation with "sectarian righteousness" prevented the establishment of a chair for natural science until 1770. And it was not until the next century that a chair of mathematics was successfully inaugurated.

Harvard and Yale (and later, Princeton) were founded by Congregationalists, and it may be said that the fortunes of mathematics at these schools were in part a product of their Puritan foundations, whereas the stricter religious principles of a Quaker variety dominant in Pennsylvania tended to suppress the subject and even opposed the creation of the institutions where it was taught. In Québec, the Jesuits dominated, with their curriculum aimed at training men for the priesthood, while English Canada, following its creation in 1760, was primarily Anglican and followed an English model. In the colonial era, higher education, and hence the possibility of formally acquiring higher-level mathematics, was thus intimately linked to the religious affiliations of the various colonies.

2 The Nineteenth Century: A Period of General Structure-Building in Higher Education and in Science

With the outbreak of the Revolutionary War in the American—as distinct from the Canadian—colonies in 1776 and the subsequent establishment of a new Republic, there was a strong motivation not only to break from the English mold but also to establish a culture that ultimately would rival those of Europe and especially England. In English Canada, however, the "'democratic' influences" in play in the United States met with an "ardent opposition" that was "widely shared in loyalist British North America" [Archibald and Charbonneau 2005, 148]. Early nineteenth-century English Canadian educational activists like John Strachan thus advocated the domestic production of mostly elementary textbooks to serve the needs of a standardized elementary and secondary educational system on an English model. Although Strachan also advocated the establishment of an actual university in Canada on the "Scottish or German" model, others, at least in the first half of the nineteenth century, expected that students who so desired would follow their secondary education in Canada with university education in England [Archibald and Charbonneau 2005, 149]. This had the effect in English-speaking Canada, at least, of adopting a model and funneling students into a system that was becoming increasingly outmoded in light of educational and scientific developments on the Continent and especially in Prussia. In French-speaking Canada, the educational model remained the Jesuit one with its orientation toward primary and secondary education, although mathematics began to figure more prominently in that curriculum from the 1830s onward [Archibald and Charbonneau 2005, 153-156].

For the United States, however, the change in orientation away from England had major consequences that were reflected in the development of: (1) agencies within the Federal government to handle specific scientific needs such as the U. S. Coast Survey founded in 1807 and the Naval Observatory founded in 1842; (2) the American Association for the Advancement of Science founded by a group of scientists in 1848 as a new national organization for the promotion of science; and (3) scientific journals such as the *American Journal of Science and Arts* founded in 1818.[11] Owing to the facts that the relative numbers of scientists were small and that science was not highly specialized, the emphasis in the first half of the nineteenth century was on the general structure-building for science as a whole. These changes were also reflected at many U. S. colleges dating from the colonial period as well as at new colleges that formed in the decades prior to the American Civil War in 1861 [Parshall and Rowe 1994, 1-51]. The case of Harvard may be taken to exemplify the types of changes that occurred relative to mathematics prior to 1876, although Harvard represents a sort of best-case scenario relative to mathematical training in mid nineteenth-century America.

Harvard began the first full century of American independence from English rule by overhauling its curriculum. Relative to mathematics, knowledge of arithmetic would be required for admission for the first time [Cajori 1890, 60]. This served to elevate the level of mathematical ability of Harvard students and to accommodate a new curriculum, this time one which drew its inspiration not from England but from the Continent and particularly from France.

Historians of British mathematics are familiar with the story of how the Analytical Society took the first steps to introduce and promote continental achievements, beginning in about 1812. As Babbage, Peacock, and Herschel, among others, spearheaded the reform of mathematics at Cambridge, at Harvard the fifth Hollis Professor of Mathematics, John Farrar, translated a number of continental texts into English for his students at Harvard.[12] This began in 1818 with his edition of *An Elementary Treatise on Arithmetic, Taken Principally from the Arithmetic of Lacroix.* Farrar also translated and printed in 1818 *An Introduction to the Elements of Algebra … selected from the Algebra of Euler.* This too was advertised as a book covering what was required for admission at Harvard.

Having treated arithmetic and algebra, in 1819 Farrar translated Legendre's geometry, and in 1820, *An Elementary Treatise on Plane and Spherical Trigonometry … from the Mathematics of Lacroix and Bézout.* In 1822 he came out with another new work, *An Elementary Treatise on the Application of Trigonometry to Orthographic and Stereographic Projection*, intended for applications in navigation and surveying. This also contained logarithmic and other mathematical tables. Over the next several decades Farrar continued to revise and enlarge his books, which sometimes ran to as many as four editions.

Of all his publications, it was the translation Farrar made (with George Emerson) of the *First Principles of the Differential and Integral Calculus … Taken Chiefly from the Mathematics of Bézout* (1824), that had the greatest impact. This presentation of the calculus had a distinct advantage over Clap's presentation of fluxions at Yale, or Maclaurin's *Treatise on Fluxions* that had been used previously at the University of

11 General structure-building also occurred in Canada in the nineteenth century, although, owing first to its colonial status and then to its status after 1867 as a self-governing dominion within the British Empire, the impetus behind such development was perhaps not as strong as in the United States. At least two general scientific societies were founded in Canada in the nineteenth century, the Canadian Institution (later the Royal Canadian Institution) in 1849 and the Royal Society of Canada in 1882. Both supported publications, with the *Canadian Journal* (later the *Proceedings* and then the *Transactions*) of the Canadian Institution being founded in 1852 and the *Transactions of the Royal Society of Canada* following in 1882.
12 On Farrar and Harvard, see the account given in [Cajori 1890, 127-133].

Pennsylvania. As Farrar noted in his introduction, he recommended Bézout's approach "on account of the plain and perspicuous manner for which the author is so well known, and also on account of its brevity and adaptation to other respect to the wants of those who have but little time to devote to such studies" [Cajori 1890, 130].

Thanks to the relentless efforts of John Farrar, his numerous translations of continental works laid an excellent foundation for teaching and the development of a curriculum of remarkably high quality. By 1830, all freshmen at Harvard read Legendre's *Elements of Geometry*, in addition to what they studied of algebra and solid geometry; sophomores studied trigonometry with applications, topography, and calculus; juniors took natural philosophy, including mechanics, electricity and magnetism; and seniors applied their mathematics in such areas of natural philosophy as optics.

The most immediate beneficiary of this emphasis upon continental mathematics at Harvard was Benjamin Peirce, easily Farrar's most successful student. Having studied mathematics with Farrar, and having proofread Nathaniel Bowditch's English translation of Laplace's *Méchanique céleste*, along with its extensive notes, Peirce had a deep appreciation for the scope and power of European mathematics. Peirce first taught mathematics as a tutor at Harvard under Farrar, but as soon as he received his M.A. in mathematics, he was given the University Professorship of Mathematics and Natural Philosophy, whereupon he "began reformulating Harvard mathematics according to his own vision" [Parshall and Rowe 1994, 17]. Like Farrar, Peirce immediately began producing textbooks for his students, but these were not mere summaries or translations of what others had written; they were replete with original results. This, however, was not the immediate blessing one might have expected, for Peirce seems to have found it impossible to adopt a clear or lucid style. In fact, his lectures were murky and impenetrable, his works "the bane of the Harvard student" [Parshall and Rowe 1994, 17].

In 1838 Harvard adopted an elective course system, which meant that all but freshmen might exempt themselves from having to take further mathematics. Under this system, there were basically three options for the study of mathematics: one a year-long practical course of study; the second, designed primarily for teachers, was to be more theoretical; and the third was to be developed over three years of study with the intention of producing professional mathematicians.[13]

The elective system at Harvard not only reduced greatly the number of students Peirce was expected to instruct, but it also liberated him from having to teach a broad range of courses to students across their four years at Harvard. When the Lawrence Scientific School for science and engineering at what was basically the graduate level was established at Harvard in 1847, this allowed Peirce to elevate even further the level of his teaching and to present more serious mathematics to his better students.

He drew up a "Course of Study in Mathematics and Astronomy" that in the first year covered curves and functions, including study of Cauchy's *Les applications du calcul infinitésimal à la géométrie*, and the *Cours d'analyse de l'École royale polytechnique*, along with Hamilton's quaternions. In the second year, students studied both Laplace's *Méchanique céleste* and Poisson's *Mécanique analytique*, along with Lagrange's *Mécanique analytique*. Gauss's theory of celestial motion was introduced, along with

13 On Peirce's educational initiatives at Harvard, see [Kent 2005].

works by Bessel, Leverrier (his work leading to the discovery of Neptune), and Adams (irregularities in the motion of Uranus, including Adams's hypothesis that it was being influenced by a more distant planet). The third year covered the theory of light, Cauchy's *Exercises d'analyse et de physique mathématique*, and Neumann's study of the reflection and refraction of light.[14]

Unfortunately, precious few students benefitted from this curriculum; in 1848, for example, there were only two [Cajori 1890, 141]. Although he failed to establish a thriving school of mathematical research, he did establish a tradition in applied mathematics at Harvard that was carried on into the twentieth century by his son James Mills Peirce, William Byerly, and Benjamin Osgood Peirce [Parshall and Rowe 1994, 19-20]. At Harvard, what Peirce accomplished, above all, was the introduction through the Lawrence Scientific School of research-level mathematics. At mid century, only Yale of the American colleges was positioned even marginally to follow suit. In Canada, on the other hand, although McGill College had been officially inaugurated in 1829, the University of Toronto had been established under that name in 1850, and the Université Laval had received a royal charter in 1852, all of these institutions offered mathematics at an exclusively undergraduate level until at least the 1890s [Archibald and Charbonneau 2005, 158-159 and 162]. Major changes followed in the United States, however, in the wake of the American Civil War (see [Guralnick 1978] and [Bruce 1987]).

3 A Mathematical *Research* Community Emerges in the United States: 1876–1900

The American Civil War, which divided the North from the slave-holding South during the bloody four-year period from 1861 to 1865, marked not only a turning point in American political history but also the beginning of a new era in the history of American higher education [Veysey 1965, 1-18]. Before the war, as we have seen, colleges in the United States had largely been controlled by conservative clergymen of various Protestant religious persuasions and had embraced the traditional classical curriculum—with its focus on Latin, Greek, and Euclidean geometry—as a means for training the mind. Although other subjects—modern foreign languages, the sciences, history—had begun to make inroads into the curriculum in the years before the war [Guralnick 1979], the goal of college education remained the production of liberally educated gentlemen, with the duty of the professor being to impart, not to create, knowledge. This was the hallmark of the colonial college.

After the war, a new generation of scholars—some of whom had been trained in Europe, some of whom had actively studied European educational systems, some of whom, like Peirce, were anxious to demonstrate that America was the cultural equal, if not superior, of Europe—sought to transplant their conceptions of the best European educational models to American shores. Their efforts, in some sense, occurred at an auspicious time. The war had created vast fortunes, and some of those newly rich—men like Erza Cornell and Johns Hopkins—decided that the needs of higher education represented a worthy target of their philanthropy. During the war, moreover, the Congress had provided Federal support—in the form of the Morrill Act of 1862—for the

14 For the complete list of courses, see [Cajori 1890, 137-138], and [Parshall and Rowe 1994, 50, Table 1].

establishment in each of the states of a university that would subsequently be state-supported and that would provide training in practical arts such as agriculture, engineering, and mining for the betterment of the nation [Dupree 1986, 149-151]. After the war, this act was extended even to those states that had broken from the Union.

Both of these new models, the privately endowed university and the so-called land-grant universities, provided opportunities for educationally reform-minded scholars—many of whom were scientists of one stripe or another—to implement their fresh ideas about the role and the goals of the American university. For them, the university should not simply provide a liberal, undergraduate education, although this should be *one* of its goals. It should *also* be a hothouse for research and for the active contribution to the store of knowledge as well as a seedbed for future researchers. The "new education" these reformers ultimately crafted, with its twin ideals of teaching and research, at the new kinds of universities they created, fostered an environment in which many areas—among them, mathematics—blossomed at the research level [Bruce 1987, 326-338].[15] The first university to create and foster a "modern" department of mathematics in the United States was The Johns Hopkins University [Parshall 1988].

Johns Hopkins was an institution born during the so-called "Gilded Age," the period immediately following the Civil War in which many businessmen who had profited from the war—men like Cornelius Vanderbilt, John D. Rockefeller, and Johns Hopkins—directed significant amounts of their newly amassed fortunes toward philanthropic concerns. In particular, they contributed to higher education and to the creation of a new category of university, the university in the modern sense of an institution devoted to higher studies and to the production of original research. For his part, Hopkins bequeathed $7,000,000 for the creation of a university and a medical school, although he specified neither a plan nor a philosophy for the new school. That task fell to Daniel Coit Gilman, the university's first president and one of the new generation of American educational reformers. He was thus in the position of creating a university *de novo*, and he had distinct ideas. As he wrote,

> what is wanted in Baltimore is not a scientific school, nor a classical college, nor both combined; but a faculty of medicine, and a faculty of philosophy: that the usual college machinery of classes, commencements etc may be dispensed with: that each head of a great department, with his associates in that department,—say of mathematics, or of Language or of Chemistry or of History, etc. shall be as far as possible free from the interference of other heads of departments, & shall determine what scholars he will receive & how he will teach them [Veysey 1965, 160].

Moreover, the faculty should consist of "men of acknowledged ability and reputation, distinguished in the special departments of study, capable of advancing these departments & also of inciting young men to study and research" [Hawkins 1960, 26].

15 Charles Eliot, the president of Harvard from 1869 to 1909, actually coined the phrase "new education" in a pair of articles that appeared in the *Atlantic Monthly* in 1869 [Eliot 1869]. For him, at this moment when he was embarking on what would become his forty-year-long tenure as president, the "new education" meant primarily a curricular emphasis on the sciences, modern languages, and mathematics—as opposed to Latin, Greek, and mathematics— and not a focus on research and the training of future researchers. The latter would come to characterize the "new education" by the turn of the twentieth century.

For the department of mathematics, Gilman found a man with these qualities in the sixty-one-year-old English mathematician, James Joseph Sylvester.

Sylvester had made a reputation internationally as the developer, with Arthur Cayley, of the British approach to invariant theory. Sylvester animated a program in mathematics at Hopkins that generally centered on his own evolving research in invariant theory, number theory, the theory of partitions, and matrix theory. In his seven-and-a-half year tenure in Baltimore, Sylvester directed the studies of some sixteen students, nine of whom ultimately earned the Ph.D. for the original, if not always exciting, work in mathematics that they did in the context both of Sylvester's courses and of the research-oriented mathematical seminary that he began.[16] That research, moreover, tended more often than not to be published in the *American Journal of Mathematics*, a research-level journal founded in 1878, edited by Sylvester, and underwritten financially by the university.

The idea of a university-underwritten research journal was one of Gilman's innovations at Hopkins. As he realized, if the university were going to expect, indeed, require the production of original research from its faculty and students, it was going to have to provide a high-level vehicle for the publication of such research. Although efforts had been made to sustain specialized mathematics journals in the United States prior to 1878, these had all ended in failure, some after only a volume or two, owing to the lack either of financial support or of sufficient materials or both [Parshall and Rowe 1994, 51]. The *American Journal*, thanks to Sylvester's tireless research efforts as well as to the contributions he actively solicited from Europe, from the United States, and from his Hopkins students and colleagues, was the first specialized journal for research-level mathematics to survive in the United States, and it, in fact, thrived [Parshall 2006, 239-248]. By the late 1870s, the nation was beginning to acquire the critical mass necessary to sustain a research-level mathematical community.

But it was only beginning. When Sylvester left Hopkins in December of 1883 to take up the Savilian Professorship of Geometry at Oxford University back in his native England, his students, although trained at the research level and imbued with the research ethos, found themselves by and large with positions at traditional, teaching-oriented colleges with no resources and precious little time to pursue their own research. Although Gilman had tried unsuccessfully to secure the noted German mathematician, Felix Klein, as Sylvester's successor, Sylvester was ultimately replaced by the mathematical astronomer, Simon Newcomb [Parshall and Rowe 1994, 138-144].

In the decade following Sylvester's departure, American students who might have gone to Hopkins to work under Sylvester instead went Europe—and especially to Klein's lecture halls—for their mathematical training [Parshall and Rowe 1994, 189-259]. On their return to the United States, however, they found that other institutions had begun to follow the Hopkins model. In the 1890s, Yale and Harvard, as well as other universities like Cornell and the University of Chicago which had been founded thanks to private munificence, had begun to establish true graduate-level programs on the Hopkins model.

16 For a technical discussion and overview of Sylvester's mathematical research, see [Parshall 1988]. For a discussion particularly of his work as well as that of Story and Sylvester's students in the years from 1876 to 1883, see [Parshall and Rowe 1994, 99-138]. On Sylvester's training of students at the graduate level, see [Parshall 1988] and [Parshall 2006, 235-273].

Moreover, the new so-called “land grant” universities also followed that example relative to research and graduate study. Klein's students, unlike Sylvester's, found jobs in each of these kinds of institution in every region of the United States. They continued to do their research; they animated their own graduate-level programs in mathematics; they worked to establish new research-level journals and new societies for the promotion of mathematics.

Consider, for example, the case of the University of Chicago, a university founded in 1892 thanks to the benefaction of oil magnate, John D. Rockefeller. Its first department of mathematics, consisted of the Yale-trained Eliakim Hastings Moore as full professor and acting head and the German-trained students of Felix Klein, Oskar Bolza as associate professor, and Heinrich Maschke as assistant professor. At the graduate level in particular, they crafted a curriculum that rivaled those of some of the best universities in Germany and that aimed “to give the student a comprehensive view of modern mathematics, to develop him to scientific maturity, and to enable him to follow, without further guidance, the scientific movement of the day, and, if possible to take an active part in it by original research” [Parshall and Rowe 1994, 367]. In its earliest years, the Chicago faculty offered “courses on the most important branches of modern mathematics such as: Theory of Functions, Elliptic Functions, Theory of Invariants, Modern Analytical Geometry, Higher Plane Curves, Theory of Substitutions, Theory of Numbers, Synthetic Geometry, Quaternions, Theory of the Potential … at least once in two years, while other courses of a more special character and the Seminars [were] intended to introduce to research work” [Parshall and Rowe 1994, 367].

Moore, Bolza, and Maschke—together with Moore’s 1896 Ph.D. student, Leonard Eugene Dicskon, who joined the department in 1900—cooperated to animate the Chicago department of mathematics until Maschke’s death in 1908 and Bolza’s return to Germany two years later in 1910. Moore, whose early interests were in geometry, switched in the 1890s to group theory, then in the first decade of the twentieth century into axiomatics, and finally from the 1910s until his retirement in 1930 into functional analysis. Dickson took up the algebraic mantel from Moore, focusing on the theory of linear groups during the first of his almost four decades on the Chicago faculty. Bolza brought what he had learned at Klein’s feet on the theories of elliptic and hyperelliptic functions and integrals to his Chicago classrooms in the 1890s but then began what would become a dynasty at Chicago in the calculus of variations after 1900. Maschke shifted mathematical gears as well. From the turn of the twentieth century to his untimely death in 1908, he moved from the theory of finite linear groups into the invariant theory of differential forms. Between them, Moore, Bolza, Maschke, and Dickson had guided thirty-one students into mathematical research and to the doctoral degree by 1910 [Parshall and Rowe 1994, 423-426].

They had also given their students more than an appreciation for mathematical research. They had imbued in them a sense of the importance and desirability of working toward the development of a professional, research-level mathematical community [Parshall 1984, 321-329]. As early as 1893 and in conjunction with the World’s Columbian Exposition held in Chicago in celebration of the four-hundredth anniversary of Christopher Columbus’s discovery of the “New World,” Moore, Bolza, Maschke, and Henry White of nearby Northwestern University organized an international mathematical congress that drew Klein from Germany as the official representative of the Prussian government. Although only three other mathematicians from abroad actually attended the congress, Klein brought with him papers from some of Germany's finest mathematicians—David Hilbert, Hermann Minkowski, Heinrich Weber, Robert Fricke, among others—and other foreign mathematicians such as Charles Hermite, Adolf Hurwitz, and Salvatore Pincherle contributed papers, all of which were read at the event [Parshall and Rowe 1994, 295-330]. Moore and his co-organizers then worked to find a publisher for the collection. They approached the New York Mathematical Society, which had been founded at Columbia University in 1888 and which had begun publishing its *Bulletin* in 1891. The negotiations which ensued not only resulted in the appearance of the Chicago congress volume in 1896 but also in the renaming of the society to the *American* Mathematical Society in 1894.[17]

Moore and his Midwestern colleagues had set into motion a process that would result in a truly national—as opposed to a Northeastern—society for the promotion of mathematical research by World War I [Parshall 1984]. In 1896, they capitalized on this momentum by successfully lobbying for the creation of an official Chicago Section of the American Mathematical Society. As they conceived of them, official *sections* of the Society would allow mathematicians who were geographically removed from New York City, the location of the Society's regular meetings, to come together under the Society's auspices to publish accounts of their meetings and abstracts of their research contributions in the Society's *Bulletin*. This would more easily make known new research breakthroughs achieved outside the traditional Eastern strongholds. By 1900, moreover, Moore had also been involved in founding and editing a new, research-level journal, the *Transactions of the American Mathematical Society*, and a year later, he was elected the first Midwestern president of the Society.

That the students in the Chicago program from 1892 to 1910 imbibed from their mentors not only the research ethos but also a sense of the greater community involvement in profession-building so exemplified by Moore can be seen perhaps most stunningly in the cases of four of Moore's early Ph.D.s [Parshall 1984, 330-332]. In addition to Dickson, who came to Chicago during Moore's "algebraic period" and who went on to animate a school of algebraic research at Chicago that thrived well into the twentieth century [Parshall 2004], Moore also guided the research of Oswald Veblen, Robert L. Moore, and George David Birkhoff. Veblen and R. L. Moore came to work with Moore during his "axiomatic period" and wrote dissertations in 1903 and 1905, respectively, which dealt with devising complete and independent sets of axioms for geometry. Veblen moved on to a long and productive career first at Princeton and then at the Institute for Advanced Study, following its founding in Princeton in 1930. His efforts helped to reshape Princeton from a colonial college into a modern research university on the Chicago model, while his research in differential geometry established Princeton as an internationally recognized center in the field. R. L. Moore had a more peripatetic career, ultimately engendering, through his noted "Moore method" of mathematical instruction, a school of point-set topology from his positions first at the University of Pennsylvania and then at the University of Texas at Austin [Zitarelli 2004]. Birkhoff came to Chicago from

17 In Canada, specialized mathematical societies were founded later: the Société mathématique de Québec (founded in 1923) and the Canadian Mathematical Society (founded, although not under that name, in 1945).

Harvard when Moore was in his “analysis period” and wrote, inspired by both his former Harvard professors and by Moore, a dissertation dealing with boundary value and expansion problems of ordinary linear differential equations. After a short stint with Veblen at Princeton, Birkhoff returned to Harvard, where he embraced and significantly enhanced the research reorientation well under way there. All four of these men also served as editors of major American mathematical research journals and as president of the American Mathematical Society. They followed well the lessons of their mentors at Chicago as they worked to strengthen the American mathematical research community in the decades prior to the outbreak of World War II.

4 The Twentieth Century: The Consolidation and Growth of Research-Level Mathematics

As the careers of Moore’s Chicago students exemplify, over the period from 1900 to 1950, mathematics at the research level took hold at the new privately endowed universities, at many of the former colonial colleges, at state-supported universities, and at the land-grant institutions. In Canada, this period also witnessed a move, albeit a much slower one, toward mathematical research. Two examples should suffice to characterize this period of consolidation and growth within the context of mathematics in the United States—the example of the former colonial college, Princeton, and that of the land-grant University of California in Berkeley—while the 1924 International Congress of Mathematicians hosted in Toronto will provide a sense of developments in Canada.

At Princeton, Felix Klein's student, Henry Burchard Fine, worked tirelessly in the context of the broader reform movement initiated by Princeton president, Woodrow Wilson, to transform Princeton from a small-town school in New Jersey into an international center for mathematics in the early decades of the twentieth century. In his capacity as Dean of the Faculty, Fine oversaw the reorganization of Princeton into academic departments, and in 1904 he became the first Chairman of the department of mathematics [Rhinehart 1999, 92]. A year later, he instituted the Princeton preceptorial system, which was a variant of the tutorial system at Harvard where the most promising young scholars were appointed to the faculty and charged primarily with intensive instruction of undergraduates. Among the first preceptors whom Fine recruited were Luther Eisenhart and Oswald Veblen. Fine also attracted prominent Europeans to teach at Princeton, including the Englishman James Jeans, who was invited as Professor of Applied Mathematics, and the Scots mathematician Joseph H. M Wedderburn. Other prominent appointments at Princeton made by Fine included the Americans George D. Birkhoff and James Alexander as well as Russian-born Solomon Lefschetz [Aspray 1988].

The foundation for the transformation of Princeton into a leading national and international center for mathematics had actually been laid a decade earlier when the *Annals of Mathematics*, which had been founded at the University of Virginia in 1884, moved from Harvard to Princeton in 1899. Under the editorships of Wedderburn (in the 1910s and 1920s) and Lefschetz (in the 1930s through the 1950s), it soon became one of the most prestigious journals for the publication of research-level mathematics in the world.

Uniquely important to the future of mathematics at Princeton, however, was the creation, in 1930, of the Institute for Advanced Study [Batterson 2006]. The School of Mathematics was the first to appoint members in 1932, and was housed with the Princeton department of mathematics in Fine Hall until the Institute opened its own facilities not far from the University in 1939. Of the first members of the Institute, a number were Princeton professors, including Alexander, Veblen, John von Neumann, and Hermann Weyl. The department of mathematics at Princeton enjoyed especially close relations with the Institute, which soon joined the Department in jointly publishing the *Annals of Mathematics*, and launching the *Princeton Mathematics Series* in 1939, and the *Annals of Mathematics Studies* in 1940. One measure of the success of the Princeton department is that—despite its relatively small student population—it graduated more Ph.D.s in mathematics between 1935 and 1955 than any other university in the U. S. [Gunning 1978, 318].

If Princeton exemplifies the changes that took place relative to mathematics during the first half of the twentieth century as a result of the reforms constitutive of the "new education" that developed during the closing quarter of the nineteenth century, the University of California at Berkeley, one of the land-grant institutions, represents a very different, but equally dramatic, example of the consolidation and growth of research-level mathematics in early twentieth-century America. Following the rush westward in search of gold in the late 1840s, a rush that had made many wealthy, the California territory attracted increasingly many newcomers. By the time California officially became a state in 1850, its legislature had already made constitutional provisions for establishing what it viewed as the necessary infrastructure for this growing population. Key among those provisions was one for a state-funded university. The University of California was finally legislated into existence in 1868 after the decision was made, after much negotiation, to use the state's Federal land-grant funds to this end [Stadtman 1970, 30-34].

It took a year to put together the first faculty of nine professors and one instructor, but when the university opened its doors to students regardless of gender in the fall of 1869 two among them were mathematicians: William Thomas Welcker as professor and Frank Soule as assistant professor. Both of these men had received their mathematical training at the United States Military Academy at West Point, and neither was a researcher [Stadtman 1970, 50-52]. Research was initially not part of the university's mission. In fact, guided by an acting president and a board of regents with little real expertise in higher education, the university had little sense of mission beyond the prescripts of the Morrill Act to provide an education "somehow useful to the students in their classrooms" [Stadtman 1970, 61]. That changed briefly in 1872 when the same Daniel Coit Gilman who would accept the presidency of The Johns Hopkins University in 1875 accepted first the presidency of the University of California.

As noted above, Gilman was a recognized figure in American higher education by the early 1870s. His extensive study of and experience with institutional models in the United States and in Europe had resulted in his formulation of distinct ideas as to what the future direction of higher education in America should be, ideas he tried to implement at Berkeley. In particular, while the idea of research was inherent in Gilman's call "to advance the arts and sciences of every sort," he was also mindful that in crafting the University of California

> [i]t is not the University of Berlin nor of New Haven which we are to copy; it is not the University of Oakland nor of San Francisco which we are to create; but it is the University of this State. It must be adapted to this people, to their public and private schools, to their peculiar geographical position, to the requirements of their new society and their undeveloped resources. It is not the foundation of an ecclesiastical body nor of private individuals. It is "of the people and for the people"—not in any low or unworthy sense, but in the highest and noblest relations to their intellectual and moral well-being [Stadtman 1970, 64].

The goals were clear, but equally clear was the fact that achieving them would have to be a gradual process constrained by local circumstances.

Those local circumstances soon became all too apparent to Gilman, however. As president, he found his power to realize his vision severely curtailed by powerful and vociferous factions within the state legislature. These mistakenly viewed him as attempting to undermine the land-grant mission of providing education in the practical and useful arts through his support of a curriculum that incorporated a full range of subjects including the modern languages, history, and literature [Stadtman 1970, 67]. When Gilman left in 1875 to assume the Hopkins presidency, these issues of turf between the president and the legislature over authority over the university were still largely unresolved.

Although the closing quarter of the nineteenth century found the university in the hands of well-intentioned but lackluster presidents with little vision and little control, the program in mathematics attempted to capitalize during this time period on changes within the emerging American mathematical research community. In 1882, it secured as its new professor of mathematics, W. Irving Stringham, an 1880 Ph.D. under Sylvester at Hopkins who had pursued postgraduate study under Felix Klein in Leipzig. Eight years later in 1890, Stringham drew another of Klein's students, Mellen Haskell, to the Berkeley faculty as an assistant professor. Although both of these men had done original research—Stringham in elliptic functions and Haskell in Klein's brand of geometry—they found it difficult to maintain their research momentum in an academic atmosphere that failed to encourage it. As Stringham put it in a letter to Klein in 1888, "[t]he plants of intellectual culture grow but slowly, and on new raw ground like that of California they can hardly flourish without very great efforts" [Parshall and Rowe 1994, 266].

Mathematics finally blossomed at Berkeley in the 1930s during the presidency of Robert Gordon Sproul, despite the financial stringencies imposed on the university by the nationwide economic depression. On the advice of a hand-picked and high-powered committee, Sproul plucked Griffith Evans from Rice University in Texas and gave him the explicit task of turning Berkeley's department of mathematics into a major center of mathematical research [Rider 1989, 287-292].

Evans, a proven and respected researcher who had done seminal work on the theory of integral equations as well as in applied mathematics and mathematical economics, not only had a broad vision of mathematics but also worked tirelessly to make that vision a reality at Berkeley. After his arrival in California, Evans cooperated with the efforts of the wider American mathematical community to place displaced European scholars, securing for Berkeley the services both of Hans Lewy, a leader in the field of differential equations and formerly at the Mathematics Institute in Göttingen [Fermi 1971, 286], and of Alfred Tarski, a major force in mathematical logic. Evans further resolved that Berkeley would build a major program in statistics, and to that end, he brought to Berkeley the Polish statistician, Jerzy Neyman [Rider 1989, 293-294]. In the fifteen years from 1933 to 1948, seventeen mathematicians, a number of them world-class, joined the Berkeley department. In all, they directed some fifty-five students successfully to the Ph.D., an 83% increase over the previous fifteen-year period. By capitalizing on a supportive administration, on world events, and on his own sense of both mathematical talent and the future directions of the field, Evans had "realized the ambition of a major center of mathematical research and teaching at Berkeley" [Rider 1989, 296].

The realization of similar ambitions would also come to Canada, although somewhat later. Writing in 1932, the Hopkins-trained Canadian professor of mathematics at the University of Toronto, John C. Fields, lamented that "progress in mathematics in Canada up to the present has not been all that might have been hoped for, [but] things look more promising for the future. There is a small but increasing group of younger men who are interested in mathematical research, and some of the later appointments have been encouraging" [Archibald and Charbonneau 2005, 141]. Although only in "the years 1935–1945" would there be "distinct signs of research mathematics beginning to come to Canada" [Archibald and Charbonneau 2005, 177], such a change may be said to have been foreshadowed by the International Congress of Mathematicians (ICM) organized by Fields and held in Toronto in 1924.

The 1924 ICM had been slated for New York City and would have been, in some sense, the official début of the newly emergent American mathematical research community on the international scene. Instead, when the American Mathematical Society withdrew its support in 1922 for political reasons surrounding the ban by the International Mathematical Union on mathematicians from the former Central Powers, Fields stepped up with an offer to host the event in Canada. By bringing the ICM to Toronto, Fields not only directly exposed his countrymen to some of the best mathematics being done internationally, he also created an opportunity to draw together his farflung, mathematically-minded countrymen. In all, 107 Canadians and 191 Americans made up the 444 mathematicians present in Toronto, and the work of fifteen Canadians was represented by papers or abstracts in the Congress proceedings. Although much of that work may not have been "at the leading edge of research," it still reflected that mathematical research was being done in Canada in the 1920s [Archibald and Charbonneau 2005, 173].

5 The North American Mathematical Landscape by 1950

The first five decades of the twentieth century witnessed the consolidation and growth of a North American mathematical research community in the context of a reorientation of higher education [Parshall and Rowe 1994, 427-428; Archibald and Charbonneau 2005, 142]. In the United States, this had been influenced significantly by the endowment of new universities like The Johns Hopkins, Clark, and the University of Chicago in the closing quarter of the nineteenth century. These universities, led by men influenced by their astute observations of the evolution of the liberal arts colleges in the United States as well as of educational models abroad, set a new standard for American higher education at the same time that they played a critical role in the professionalization of the various academic disciplines. In mathematics, their departments led the way in graduate training and, in the cases of Hopkins and Chicago, in undergraduate training as well. Their leaders, men like Sylvester, Story, and E. H. Moore, also recognized the need to establish the accoutrements of a mathematical *profession*—journals, seminars, congresses, societies—and they worked to realize these goals within institutional settings perfectly conducive to and supportive of their efforts.

Long-established institutions like Harvard, Yale, and Princeton reacted to the stimulus these upstarts provided, and this was also true of the newer, nineteenth-century models of state-supported and land-grant schools like Cornell, Michigan, Wisconsin, and Berkeley. In mathematics, this translated into the formation of research-oriented departments from coast to coast actively and successfully involved in training future generations of researchers.

The story, while different chronologically by almost a half-century, was nevertheless parallel in Canada. When many of Europe's best mathematicians were forced by the political events of the 1930s and 1940s to flee their homelands, the fact that they were able to establish themselves almost immediately in an environment in North America that fostered their research bore testament to the fact that "[t]he level of mathematical activity in America was comparable to that brought to America by the newcomers" [Bers 1988, 238] and that Canada was not that far behind [Archibald and Charbonneau 2005, 177]. The raising of the mathematical bar, particularly in the United States, to a level that had made the country not only competitive but a leader internationally by 1950 owed in large measure to the emergence of the research university.

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