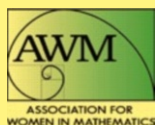


Association for Women in Mathematics Series

Janet L. Beery
Sarah J. Greenwald
Jacqueline A. Jensen-Vallin
Maura B. Mast *Editors*

Women in Mathematics

Celebrating the Centennial of the
Mathematical Association of America



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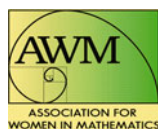
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Editors

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Preface

Women in Mathematics: Celebrating the Centennial of the Mathematical Association of America presents a collection of papers on the contributions, achievements, and progress of women mathematicians, mostly in the twentieth and twenty-first centuries, emerging from the themed contributed paper session “The Contributions of Women to Mathematics: 100 Years and Counting” at MathFest 2015, sponsored by the Association for Women in Mathematics to celebrate the 100th anniversary of the Mathematical Association of America. As such, the collection contains a diverse mix of current scholarship and exposition related to women and mathematics rather than a balanced coverage of women during this time period. This volume is intended to be an interconnected collection of biographies, histories, studies, reflections, cultural discussions, and other articles related to women in mathematics, primarily but by no means exclusively in the English-speaking West. The articles provide compelling, interesting, and informative reading for mathematicians, historians of science, teachers of mathematics, and students at the high school, college, and graduate levels, and in general anyone interested in attracting more girls and women as students, faculty, and/or employees.

It is an opportune time to look back at the accomplishments of women in mathematics. Mathematical culture has subtly shifted over the past century and certainly during our lifetimes. Some of the visible indicators include a greater number of women filling tenure-track and tenured academic positions, receiving prestigious awards and honors, being invited to give plenary addresses, serving in leadership positions in professional societies, and, in general, being more visibly active in the mathematical community. There are far too many notable moments to list, but here are a few related to women in mathematics in the USA that have inspired us personally:

- 1886—The first woman known to earn a PhD in mathematics in the USA was Winifred Edgerton Merrill, from Columbia University.
- 1932—Emmy Noether delivered the first plenary lecture by a woman at the International Congress of Mathematicians, a year before she moved to Bryn Mawr College in the USA.

- 1943—The first minority woman known to earn a PhD in mathematics in the USA was Euphemia Lofton Haynes from the Catholic University of America.
- 1971—Mary Gray of American University was the first chairman/president of the newly founded Association for Women in Mathematics.
- 1976—Julia Bowman Robinson of the University of California, Berkeley, was the first female mathematician elected to the National Academy of Sciences, one of the highest awards a scientist can receive.
- 1998—Melanie Wood of Park Tudor High School in Indianapolis became the first female member of the US team for the International Mathematical Olympiad, going on to earn a silver medal.
- 2014—Maryam Mirzakhani of Stanford University was the first woman to be awarded a Fields Medal, one of mathematics' highest awards.
- 2015—Katherine Johnson, retired from NASA, was the first female mathematician to earn a Presidential Medal of Freedom, the highest civilian award in the USA.

Despite women's gains, we know that not all mathematics students have access to strong role models or opportunities to engage with female mathematicians at conferences, at workshops, or on their local campuses. Three of us remember the thrill of meeting a female mathematician for the very first time. For Janet, the mathematician was Gloria Hewitt, who delivered a pitch-perfect talk on group actions just as Janet was taking the abstract algebra sequence at her undergraduate institution. (Hewitt had advised the PhD dissertation of one of the mathematics professors there and visited the campus at his invitation.) Sarah began her undergraduate career as an engineering major but was also interested in mathematics. So she looked for someone to talk to and happened upon Susan Niefeld, a category theorist, who would later become her advisor, mentor, and much more. Sarah's mom died later that year—from driving her to the train station to helping her navigate through financial aid and other issues, Niefeld was instrumental in helping Sarah stay in school and encouraging her interest in mathematics. Jackie added a mathematics degree late in her undergraduate career and so first encountered a female mathematician, Marie Vitulli, at the University of Oregon as a PhD student. Marie challenged her students and held them to high standards. Marie also lobbied vociferously for excellent female job candidates to expand the number of role models available to women at U of O. Maura's father was a mathematics professor at Notre Dame, so she grew up knowing (a few) female mathematicians. In her senior year at Notre Dame, she was thrilled to take a graduate course on mathematical logic with Julia Knight.

We hope that this volume will provide inspiration to its readers, showing them how women have made substantial contributions, as individuals and as groups, to mathematics research, mathematics education, mathematical culture, and outreach, and inspiring them, in turn, to encourage women and girls to pursue mathematical careers. It contains some biographies of women in mathematics, but not the typical set of "famous" biographies. Instead, the volume features diverse biographies of women, including some who made a difference in ways that might at first glance

seem small but were significant either for their time or for the individuals who were influenced by these women. Articles take the form of a focus on individuals, groups of students or women, groups that include women, or other connections. Some articles update and expand work on women in mathematics previously published. The book also contains expository articles and showcases how the role of women in mathematics has changed over time. As the conference session at MathFest 2015 celebrated active scholarship by women in mathematics, so too does this volume. The diversity of topics and multiplicity of authors of individual articles ensures a wide variety of perspectives. We hope you enjoy reading these chapters as much as we have.

We are grateful to the individuals and organizations that supported the formation of this volume. Alissa Crans was co-organizer, along with Maura and Jackie, of the paper session that inspired this volume and we owe her tremendous thanks for contributing to the original vision of promoting contributions by women to mathematics. We thank our dedicated and talented chapter authors, six of whom participated in this paper session and all of whom devoted significant time and energy and brought considerable passion and skill to their contributions to this volume. We also thank the wonderful referees who graciously helped us shape the articles in this collection. Fordham College at Rose Hill administrative assistant Susan Legnini provided organizational and administrative support in the early stages of this project, and Sarah Duncan, doctoral candidate in clinical psychology at Fordham, assisted with typesetting and proofreading a number of the chapters. We have all been inspired by the leadership of AWM past president and AWM-Springer series editor Kristin Lauter, who provided important early encouragement to us to organize this volume. We also appreciate the advocacy and community of the Association for Women in Mathematics; for all of us, our involvement with AWM has been fundamental in the development of our mathematical careers. Finally, we extend deep thanks to all of the women in mathematics who have come before us: they are the ones who made this book possible.

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June 2017

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Part I
Groups of Women United by a Historical
Event, Institution, or Cultural Tie

Chapter 1

Fostering Academic and Mathematical Excellence at Girton College 1870–1940

Shawnee L. McMurrin and James J. Tattersall

Abstract Founded in 1869, Girton College, Cambridge was Britain’s first residential college for women to offer an education at degree level. At the end of the nineteenth century, women’s colleges such as Girton played a significant role in improving girls’ education. In its early years, women often came to Girton underprepared for university studies, particularly in mathematics. Determined to prove their merit, women at Girton found creative ways to hone their mathematical skills, an essential undertaking especially for those women preparing for the formidable Mathematical Tripos exam. Along with British and international mathematicians, several Girton students contributed to the mathematics department of *The Educational Times and Journal of the College of Preceptors*. During the first half of the twentieth century, as research mathematics flourished and the preparation of its students improved, Girton continued to provide support and encouragement for women pursuing mathematical and scientific studies through its research fellowships. We detail the accomplishments of several women who, influenced by Girton’s commitment to academic excellence, went on to play prominent roles in private and public sectors.

Keywords Girton College • Cambridge • Women’s colleges • Mathematical Tripos

1.1 Introduction

There is no tool for development more effective than the education of girls and the empowerment of women . . . When women are fully involved, the benefits can be seen immediately: families are healthier; they are better fed; their income, savings, and reinvestment go up. And what is true of families is true of communities and, eventually, whole countries. [1]

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Such arguments abounded in the nineteenth century as reformers battled for women's educational rights. In some places, the battle continues. The quote comes from Kofi Annan's 2004 keynote address for the International Women's Health Coalition.

The question of who should have access to formal education, and to what extent, has been asked and argued for centuries. Here we consider the question of access to higher education for women through the lens of one of the Britain's ancient universities, Cambridge, an institution where, historically, gender equity was particularly slow to take hold, especially in the field of mathematics.

In thinking about mathematics at Cambridge, one naturally calls to mind its iconic scholars such as Isaac Newton, John William Strutt (Lord Rayleigh), George Stokes, Arthur Cayley, G.H. Hardy, J.E. Littlewood, Srinivasa Ramanujan, Paul Dirac, and any number of other illustrious academics. Yet, even today, it is the rare woman who is included on such a list.¹ Although the origins of Cambridge University date back to the Middle Ages, it was not until 1947 that the university voted to admit women to degrees and full status, making it the last British university to fully permit women into its ranks.² By that time, women had been studying at Cambridge for nearly 80 years.

Why so reluctant? It is impossible to pinpoint a single reason. Motivation for change and its opposition is as varied as the dons of Cambridge. Some argued that a woman's mind was inferior to that of a man's. A contending argument was that a woman did not have the physical stamina to withstand strenuous mental studies and engaging in them might endanger her health. Yet, even when such myths were debunked, Cambridge's opposition to full status for women held firm. After World War I, there was some concern that women with degrees would be better positioned to compete for jobs. Yet, each time the subject was broached, the primary objection centered on power. Admitting women to degrees would give them the right to participate in the university's decision-making process, a power that many Cambridge graduates were unwilling to bestow. Such resistance may have stemmed from the androcentric nature of the Cambridge experience. During the nineteenth century, those men attaining the highest honors at Cambridge were considered by the upper echelons of society to embody the epitome of masculinity. Through discipline in both mind and body, honors candidates competed to prove themselves worthy of an influential role in society. The university seemed unquestionably a male institution.

¹In 2017, Wikipedia's "List of Cambridge Mathematicians" included only two women: Mary Cartwright and Frances Kirwan [45].

²Full membership for women in the university was approved in December 1947 when Girton and Newnham were admitted as colleges of the University. Queen Elizabeth was granted an honorary degree making her the first Cambridge woman graduate. Undergraduate degrees for women were first awarded in 1948 [40]. Even after admitting women to degrees, the university did not adopt a formal policy of equal opportunities until 1987, and meanwhile retained its power to limit the number of female students, even though it did not have the right to do so for men [28, p. 187].

Still, the question persisted, “Why not a female Cambridge scholar?” In this paper, we examine Girton College’s evolution through its first 70 years and a sampling of the college women who would not let the question rest. We consider how and why these women made their mark on Cambridge University, taking particular interest in those women from Girton College who pushed boundaries in mathematics. Many went on to break glass ceilings at universities and professional organizations after leaving Cambridge. Was there something special about their Cambridge experience that fostered their ability to do so?

1.2 Victorian Reform

Founded in 1869, Girton College, Cambridge, is one of the Britain’s oldest residential colleges for women and the first to offer a university-level education for women. It was founded in the midst of the Victorian reform movement, which included an insistent call for improvements in women’s education. The stage had been set with the founding of Queen’s College, Harley Street, opened in 1848, followed a year later by The Ladies’ College, Bedford Square.³ With similar goals of elevating the education of women, the colleges that opened prior to Girton’s founding offered courses at the secondary and advanced secondary levels.

Girton’s founders, Emily Davies, Barbara Bodichon, and Lady Stanley of Alderley, staunch advocates of women’s rights, not only championed a woman’s right to higher education, they believed that women should have access to the same educational opportunities as men. To the modern mind, this seems a natural and noble aim. In Victorian England, even among reformists, this was a revolutionary, and often controversial, idea. Although the three women had attained some measure of influence in British society, certainly helpful in advancing their cause, it seems that necessity, rather than idealism, provided the strongest impetus for improving the education of women.

According to the mores of nineteenth century England, daughters of middle-class professional men were considered gentlewomen. During the early part of the century, a typical middle-class girl was raised with the primary goal of securing a suitable husband. Her education was often limited to learning to read, write, and display various “accomplishments” such as embroidery or music [28, p. 8].

As the middle-class population grew, the number of suitable—and willing—prospective husbands dwindled dramatically. According to the 1851 census report for England and Wales [29], the excess of women over men in the 25-plus age group was at about 4%. In the breakdown by marital status—single, married, or

³The Ladies’ College, later to become Bedford College, soon found that its students were inadequately prepared for a higher course of study and instituted a preparatory school to address the issue. It had no full-time teachers until the late nineteenth century, and became a constituent school of the University of London in 1900.

widowed—about 20% of women in the 25-plus age group were reported as single.⁴ The growing demand for higher education and suitable employment suggests that a significant proportion of these single women were from the middle class. One contributing factor may be that a considerable number of middle-class men were content bachelors, reluctant to take on the added expense of a wife and family [28, p. 8]. At the same time, the earnings of middle-class professional men were insufficient for supporting their growing numbers of unmarried daughters. When a young middle-class woman found herself in the unexpected position of having to support herself, socially suitable positions for which she might be qualified were limited. Although a position as a genteel shop assistant might be considered appropriate, a young woman's lack of fundamental arithmetic skills, which was generally the case, would make her an unlikely candidate. A popular alternative was to seek employment as a governess or teacher, a position for which her social status was sufficient qualification, even if her education was not. The burgeoning middle class came to recognize that, since the earliest education of its children began at home, a sound elementary education would be of benefit not only to a daughter who might eventually support herself, but also to one who would manage her own household and contribute to the education of her children.

As reform for elementary and secondary education gained momentum, it stimulated the campaign for women's access to higher education. The feasibility of the Girton "experiment" became possible, in part, via the groundwork laid by three influential groups that were very much involved in education reform: the Governesses' Benevolent Institution, the College of Preceptors, and the Royal Commission on Secondary Education.

The movement to train teachers and grant certificates of proficiency in England was pioneered by the Governesses' Benevolent Institution (GBI). Founded in 1843, the GBI recognized the growing need to prepare prospective governesses. The group realized, as we do today, that in order to engage in effective pedagogy, educators require content understanding beyond that of the level they are expected to teach. As a start, the GBI promoted the creation of a training college for governesses. In 1848, the GBI was instrumental in the establishment of Queen's College London. The college offered day and evening courses, taught at the advanced secondary school level, to girls over the age of 12. Many of its classes were taught by the staff at King's College London. In 1853, Queen's College became the first school to be granted a charter by an English sovereign for the furtherance of women's education.

Still, the basic education of a middle-class girl was so insufficient that most could not attain the standard required for a Queen's scholarship. In the view of the GBI, the only way to raise the quality of governesses was to improve education for all middle-class girls.

Meanwhile, not only the education of girls, but British education in general, especially that of the middle class, became a growing concern. The country's view

⁴The percentage of single men in the 25-plus age group was 20.3%. In the 1861 census, the percentages dropped to about 19% and 18% for single women and men, respectively.

of teaching was undergoing fundamental changes with a push to acknowledge and recognize teaching as a profession.⁵ In 1846, a group of dedicated private schoolmasters founded the College of Preceptors (CP). Their aim was to regulate teaching and promote sound learning by providing the means to better prepare teachers, raise their status, and ensure their qualifications. The CP desired to advance the interest of education among the middle class and facilitate better communication between teachers and the public. In 1849, the CP was incorporated by a Royal Charter that empowered it to hold examinations that, when passed satisfactorily, would lead to the granting of diplomas and certificates of proficiency to persons of both genders. In addition to offering periodic examinations for certification to both students and teachers, the CP offered training to those desiring to enter the teaching profession, formed a teachers' union to make provisions for families of deceased, aged, or poor members, and, at monthly meetings open to the public, promulgated announcements and summaries of important educational movements and read papers on the theory and practice of education. The College of Preceptors remains the oldest extant teaching association in the United Kingdom.

In 1864, Queen Victoria appointed a dozen men as her Royal Commission on Secondary Education (often referred to as The Schools Inquiry Commission) tasked to conduct an inquiry into the education provided at a wide range of English schools serving the middle and upper classes.⁶ Emily Davies prompted the Commission to include the investigation of conditions and education at girls' schools. The Commission's report of 1868, referred to as the Taunton Report, clearly concluded, "... the state of Middle Class Female Education is, on the whole, unfavourable [5]." It went on to provide evidence that the secondary education provided for middle-class girls was, in general, superficial and woefully inadequate, consisting mainly of French, music, and domestic industry. The report noted its "... support of the opinion that an educated mother is even of more importance to the family than an educated father ..." and proposed that a genuine effort be made to grant girls access to education that was on a par with that of boys. In particular, an effort should be made to raise standards and systematize teaching at existing schools, open entrance examinations to girls, and give them access to higher education. The administration of entrance examinations had been initiated by Cambridge and Oxford in 1858.⁷ These "local" examinations were given throughout Britain and were used both by administrators, to check on the quality of teaching in secondary schools, and by students, to gain entry into colleges and military academies.

⁵At the time, census enumerators classified teaching as a "learned occupation." In Britain's 1861 census, teaching was reclassified as a profession, which would have been considered a more prestigious category [14, p. 973]. A major factor leading to reclassification was likely the specialized training being offered to teachers along with various means for certification.

⁶Schools not included were those serving the labor class and nine of the principal schools serving boys of the middle and upper classes. Education at these particular schools had been investigated a few years previously by two other commissions [5].

⁷Delve has argued convincingly that the CP's inauguration of school examinations led to the formal establishment of entrance examinations to Oxford and Cambridge [15].

As it turns out, the examinations also played a major role in advancing women's education. The Taunton Report provided Davies with the influence needed to convince the board of examiners at Cambridge to allow women to sit for the qualifying exams. She found a number of examiners willing to grade the women's exams, albeit unofficially. It soon became evident that women could perform as well as men on the exams. Thus, women had successfully wedged a foot in the door.

1.3 Girton's Beginnings

The College for Women at Benslow House, as Girton was originally called, was located at Hitchin in Hertfordshire, about midway between Cambridge and London. All candidates were required to pass an entrance examination. In July 1869, eighteen candidates sat for the first entrance exam in London. Of those, 13 passed and two scholarships were awarded. Five went on to Girton. The college opened its doors to its first class, the five "Girton pioneers," on October 16, 1869. The first scholarship went to Isabella Townshend⁸ for excellence in writing and the other to Sarah Woodhead for excellence in mathematics. Woodhead would earn marks at the level of second-class honors on the 1873 Mathematical Tripos,⁹ becoming the first woman to sit and pass a Cambridge tripos examination [7, p. 45]. An additional student joined the class during the winter of 1870. By 1873, the college housed 15 students.

The attitude of Girton's pioneering students says much about their dedication. One student, Louisa Lumsden, "... on being asked during her first term at Hitchin what was the uppermost feeling in her mind answered 'Gladness'. She said she had a happy life at home but Hitchin brought the one thing she had been lacking in her life—aim [35, p. 31]."

Although Emily Davies had no experience working for examinations, nor any notion of the self-governing nature of a college, she was very persistent, had loyal supporters, and possessed an indomitable spirit. From the beginning, her expectation was that the institution would be a real college and not simply another school for girls. It soon became clear that this would be a difficult goal to achieve. For one, it was difficult to entice Cambridge tutors to make the 26-mile journey to the isolated school. Yet, Davies somehow managed to recruit a respectable line-up of Cambridge

⁸Isabella Townshend achieved marks equivalent to first-class honors on the 1870 Previous Exam, an exam used to determine whether a student would be allowed to proceed with a course of study at Cambridge. She left Girton in 1872 and went to Rome to study painting. She died in 1882 of typhoid fever contracted at Capri.

⁹Successful performance on a tripos exam was required to earn an honors degree from Cambridge. (See page 10.) Although a woman's performance on a tripos might earn marks equivalent to those required for particular honor's class, she would not have received official recognition for her performance, nor was she eligible for a degree.



Fig. 1.1 Photograph of the first building, now part of the Old Wing, circa 1872. Courtesy of the Mistress and Fellows, Girton College, Cambridge.

teachers for her inaugural class.¹⁰ It was not long before funds were raised to buy acreage closer to the university in the town of Girton, about three kilometers from the center of Cambridge. In 1873, after construction of the first building, the school moved and was renamed Girton College (Figure 1.1).

Although the relocation of the college improved access to lectures and tutors, the obstacle of under-preparation proved to be more problematic. Women simply had significantly less preparation than men when they came up to Cambridge. At the university, “lectures for ladies” provided one opportunity for a gentle introduction to university coursework. Initiated by utilitarian philosopher and economist Henry Sidgwick, and first offered during the Lent term of 1870, the lectures proved to be quite popular, drawing an initial attendance of 70 to 80 women. Courses of study included subjects such as English history, arithmetic, Latin, and political economy

¹⁰The first mathematics lecturer to visit was James Stuart, a fellow of Trinity College [16]. According to a letter to Marion Bradley, the list of teachers included J.R. Seeley, Regius Professor of Modern History and head of the classics tripos, J.F. Hort, an examiner for the moral science tripos, John Venn, a lecturer in moral science, logic, and probability known for introducing the Venn diagram used in set theory, George Liveing, who held the St John’s College Lectureship in Chemistry, and Joseph Lightfoot, a theologian and Cambridge graduate who, in 1851, received first-class honors on both the Mathematical and Classics Triposes [12, p. 310].

[28, p. 43]. In 1871, in order to expand access to the courses, Sidgwick arranged to provide lodging on Regent Street for those women who could not travel to and from Cambridge to attend the lectures. His gesture was the impetus for the establishment of Newnham Hall in 1875, becoming Newnham College in 1880, the second residential college for women. Originally, Newnham offered women a flavor of the Cambridge experience without the expectation that they meet the demands required for a degree.

Davies' philosophy differed vastly from that of Sidgwick. In her view, only by following the traditional Cambridge curriculum and adhering to those requirements applicable to male undergraduates, would women establish proof of their intellectual capability. She was resolute in her curriculum requirements and unwavering in her belief that her students could, and would, overcome any deficiencies in preparation.

Davies' route to success lay in a commitment to excellence in teaching. She arranged for a number of Cambridge faculty members to come to Girton to lecture, tutor, and prepare students for examinations. Teaching was adapted to help students catch up to the Cambridge men. Attending lectures at the university was a bit more troublesome since Girton students required permission from the lecturer. In the early years about half of the Cambridge lecturers allowed women to attend their university classes, with an increasing number of lecturers following suit as time went on.

Although the college would admit students who might attend for only a few terms, those students opting for the full program were held to the same standard as a Cambridge honors degree candidate and were expected to complete their course of study in the same ten-term time frame as that set for men. In order to attain a degree at that time, Cambridge students had various hurdles to cross. The first was the Previous Examination, or Little-go, a preliminary examination taken to demonstrate that a student had a basic command of mathematics and classics. In 1869, the subjects included one of the four gospels in the original Greek, Paley's *Evidences of Christianity*, Latin and Greek classics and grammar, arithmetic, and Euclid's *Elements*, books I, II, III and part of VI [38, p. 7]. By 1876, the exam was administered in two parts and the mathematics portion had been expanded to explicitly include algebra, in addition to a greater selection of geometry from the *Elements*.¹¹ The mathematics portion proved especially daunting for many Girton students.

After passing the Little-go, Cambridge men had two options. As described by Brooke [8, p. 309], "The unambitious could then go on to the pass degree, a disorderly collection of fragments of learning, the haven of the 'poll men'. The reading men went on to honours, which by 1870 meant the Mathematical Tripos, classics, moral or natural sciences . . ." The Mathematical Tripos carried with it the greatest prestige. Its origins can be traced to the fifteenth century when the examination was actually a disputation led by a moderator who sat on a three

¹¹Algebra first makes an explicit appearance in 1870 in a footnote stating, "Algebraical symbols may be employed in the solution of the questions in Arithmetic [39, p. 7]."

legged stool, or tripos.¹² By the latter part of the eighteenth century, the exam had transitioned from an oral exam to a grueling multi-day written exam. At the completion of the exam, successful honors candidates were divided into three groups: wranglers (first class), senior optimes (second class), and junior optimes (third class).

In order to prepare for the exam, Cambridge men would not only train their minds, they would also exercise their bodies in order to build up the stamina necessary to withstand the pressures of the exam [43]. Those vying for an honors degree hired coaches to help prepare responses for the multitude of exam questions that could be expected, while also engaging seriously in competitive sports and other athletic activities. Success on the exam was considered a reflection of virility. Indeed, one argument against opening degrees to women was the belief that the competitive and strenuous nature of preparing for the exam was simply too taxing for a woman's delicate constitution.¹³

Girton challenged this view. Living up to Davies' expectations, women proved that they had the wherewithal to meet the demands of the Cambridge honors curriculum by facing both the Little-go and one of the formidable tripos exams.¹⁴ As with the men, passing the Mathematical Tripos garnered the greatest prestige. All five of Girton's pioneers from the first class passed the Little-go and three succeeded in completing the entire course of study, including a successful performance on a tripos exam.¹⁵ Their success no doubt bolstered the determination of those who followed.

However, the battle was by no means easily won. In particular, the Little-go presented a tremendous challenge for many Girton students. Most men had come up from boys' schools that provided specific preparation for university, in particular, with training in Latin, Greek, and mathematics. Thus, most male undergraduates had either met qualifications that exempted them from the exam or took the exam by the end of their first year. On the other hand, as was noted in the Taunton Report, it was unlikely that a girl would have had any serious instruction in such topics at school, although some girls did receive various degrees of preparation from home tutoring. Many women required a second year to adequately prepare for the Little-go, leaving

¹²For more on the early history of the Mathematical Tripos exam, please refer to [31].

¹³Warnings from the medical profession that rigorous study could be detrimental to a woman's health were taken seriously. Davies' concern led her to include medical facilities in Girton's 1876 expansion. In 1887, research into the health of Oxford and Cambridge women was conducted. The conclusion of the extensive statistical study was that "... there is nothing in a university education at all especially injurious to the constitution of women, or involving any greater strain than they can ordinarily bear without injury [34, p. 91]."

¹⁴Women were not permitted to sit exams for a pass (ordinary) degree, even informally, so that course of study was not an option at Girton.

¹⁵In addition to Woodhead's performance at the level of second-class honors on the Mathematical Tripos; Rachel Cook and Louisa Lumsden passed the classics tripos at the levels of the second and third class, respectively. The other two members of the "Girton five," Anna Lloyd and Emily Gibson, did not sit for a tripos.

them with much less time to prepare for a tripos exam, which was usually taken after the tenth term.¹⁶ As an additional burden, until 1882, women would prepare under the uncertainty of whether or not they would be allowed to take either the Little-go or a tripos exam. Each year, Girton students were permitted to take Cambridge exams only by courtesy of the male examiners. Fortunately, there were always some examiners willing to permit women to sit exams. Women candidates would gather at an appropriate location, originally the University Arms Hotel, and wait for a messenger to bring them copies of the examination. Completed exams were then marked only informally. The first significant changes for women taking the tripos occurred in 1880 when Charlotte Scott of Girton achieved marks at the first-class honors level on the Mathematical Tripos. Her achievement led to the formal admittance of women to such examinations, with their results announced publicly.

Regrettably, women who completed the program of study at Girton and were successful on both the Little-go and a tripos were denied Cambridge degrees. This situation was a cause of considerable hardship for women seeking academic employment. Many of the best teaching and administrative positions required the applicant to be in possession of a college degree. In order to obtain such a degree Girton women had to pass an examination from a college or university that offered external degrees. In 1878, the University of London began awarding college degrees to those women who had passed a tripos examination.¹⁷ In 1904, Trinity College, Dublin followed suit. From 1904 to 1907, over 700 women, affectionately referred to as the “steambot ladies,” crossed the Irish Sea to obtain a Bachelor’s or Master’s degree from Trinity. The arrangement was profitable for Trinity as the degree fees helped fund the construction of a residence hall for women [9].

Toward the end of the century, Girton and Newnham instigated a vigorous campaign for degree status, but were voted down in 1897. Opponents of the movement were particularly worried that if women were granted BA degrees, they would then, like the male graduates, eventually be eligible for MA degrees, which included the right to vote on university affairs. Progress was slow for the next two decades. In 1921, Cambridge University conceded to the granting of titular degrees¹⁸ for women and permitted access to lectures by right rather than only as a privilege. In 1922, encouraged by Oxford’s admission of women to degrees, Cambridge women revived their campaign for degrees, but were again voted down. However, in 1926, women were allowed to assume university posts. It was not until

¹⁶The Cambridge academic year consists of three terms, Michaelmas, Lent, and Easter. Each teaching term is approximately eight weeks long. Until 1882, the Mathematical Tripos was given in January. New regulations adopted in 1882 created Parts I and II of the Mathematical Tripos administered in late May or early June. Men seeking honors were required to take Part I no later than the end of their ninth term.

¹⁷Established by Royal Charters in 1836 and 1837, the University of London served as an examining board with the right to confer degrees. In 1878, it became the first university in the United Kingdom to admit women to degrees.

¹⁸Such degrees did not confer any of the privileges of a Cambridge graduate such as membership in the university or voting rights.

1948 that women were allowed to become full members of the university. By that time graduates had much less influence on university affairs. Women were first admitted to men's colleges in 1972.

1.4 Girton Scholars

Since many of Girton's early students were in need of improving their mathematical foundation, in addition to tutoring, students would often endeavor to hone their mathematical skills via a variety of practice problems. An excellent source of problems could be found in the mathematical department of *The Educational Times and Journal of the College of Preceptors* and its offshoot journal *Mathematical Questions with Their Solutions from the "Educational Times."* *The Educational Times* was a long-lived pedagogical journal first published in the fall of 1847.¹⁹ In addition to its popular column devoted to mathematical questions and their solutions, the publication contained notices of available scholarships, an extensive list of positions for teachers and governesses, transcripts of papers read at monthly meetings of the CP, and articles on prominent educational issues. The journal also contained lists of successful candidates on examinations given by the CP, as well as questions from the latest examination along with their answers.

As part of their preparation for the Mathematical Tripos, two of the Girton's students, Sarah Marks and Charlotte Scott, teamed up to form the Girton College Mathematical Club. Its members would seek out practice problems and endeavor to "answer any mathematical questions that may arise." In addition to using the *Educational Times* for study, the women began submitting their own contributions. During the period from December 1878 to July 1904, over 75% of the nearly 350 contributions made by women to the *Educational Times'* mathematical department were attributed to women from Girton.²⁰ Eight particularly avid contributors, responsible for just over 30% of all contributions by women during the existence of the mathematical department from 1848 to 1915, were Marks, Scott, Kate Gale, Margaret Meyer, Emily Perrin, Margaret Evans, Isabel Maddison, and Frances Cave-Browne-Cave. Their clever solutions, as well as some of the ingenious problems they posed, indicate that these women were developing solid foundations in algebraic, geometric, and analytic reasoning comparable with that of the Cambridge men. All successfully passed the Mathematical Tripos. Each went on to contribute to mathematics, science, or education, and most continued to do so well into the twentieth century.

As we look briefly at the stories of some of Girton's more mathematically inclined alumni, we notice that the paths chosen to carry on Girton's legacy varied.

¹⁹The journal's original title was *The Educational Times: A Monthly Stamped Journal of Education, Science, and Literature*.

²⁰Data estimates come from the research of James Tattersall, as well as the *Educational Times'* mathematical department database being compiled by Sloan Despeaux at Western Carolina University.

Fig. 1.2 Charlotte Scott (1858–1931). From the Tucker Collection, Courtesy of the London Mathematical Society.



Many alumni pursued teaching careers, while some took advantage of opportunities to engage in research or apply their skills in research communities. We begin with Scott and Marks, who would become renowned researchers in their respective fields.

Born in Lincoln, England, in 1858, **Charlotte Angas Scott** (Figure 1.2) did much to set the stage for tripos success. Scott came to Girton in 1876 as a Goldsmiths' Scholar²¹ with a promising educational background. The second of seven children, Scott had the good fortune to have parents who were nonconformist Christians with forward-thinking views. Her father and grandfather were both ministers of the Congregational Church, a church that supported many reforms, including support for women's rights [23]. The tutoring Scott received at home provided her with a strong mathematical background and prepared her well for advanced study at the university.

Girton had grown in the seven years prior to Scott's arrival as one of an entering class of eleven students and 33 students in residence altogether. As expected, Scott excelled at her studies and, in preparation for the 1880 Mathematical Tripos, she hoped to engage one of the Cambridge's leading coaches, Edward Routh. He declined, ostensibly due to other commitments [44, p. 281]. The true motive may have been a bit different. The reputation and fees garnered by a tripos coach were commensurate with the success of his students. Since women, as a rule, were

²¹The scholarship, £60 per annum for three years, was awarded by the Goldsmiths' Company of London on the basis of Girton's entrance examination results.

deemed less likely to succeed on exams, engaging top coaches became particularly difficult. Nevertheless, Scott's potential for success was recognized and she was able to adequately prepare with coaching from Ernest Temperley and George Walker, both from Queen's College, Cambridge.²²

As was typical for the period, the 1880 Mathematical Tripos was a fifty-hour ordeal spread over nine days. It contained 210 questions, many with several parts. The exam covered algebra, geometry, analytical geometry, probability, calculus, and the basic principles of statics, dynamics, hydrostatics, optics, and planetary astronomy. At the conclusion of the exam, Scott found herself bracketed with the eighth wrangler, making her the first woman to achieve the level of first-class honors on a tripos exam. As the moderator, Temperley, prepared to read out the name of the eighth wrangler, there was a pause. A loud chorus rang out throughout the Senate House, "Scott of Girton!" That year the senior wrangler was Joseph Larmor, later Lucasian professor of mathematics at Cambridge. Second wrangler was J.J. Thomson, who, in only four more years, would be elected as the Cavendish Professor of Physics at Cambridge and would eventually win the Nobel Prize in Physics. As mentioned previously, Scott's achievement motivated changes that, beginning in 1882, granted women the right to sit for examinations and allowed their results to be published with those of the men.

Scott remained at Girton until 1885 serving as a lecturer in mathematics, where she taught as many as 33 hours a week [6]. She attended Arthur Cayley's lectures on modern algebra, Abelian functions, number theory, semi-invariants, and the theory of substitutions, and did her doctoral research in algebraic geometry under his supervision [32]. She took her DSc degree with honors from the University of London in 1885, becoming the second woman to receive a doctorate in England²³ and the second European woman, after Sofia Kovalevskaya, to receive one in mathematics.

Like most women students, during her time as student and lecturer, Scott engaged in pastimes other than mathematics. Like the men, Girton women complemented their studies with physical activity, albeit their need to present proper decorum did require them to engage in such activities discreetly (Figure 1.3). Popular activities included walking, croquet, badminton, gymnastics, and lawn tennis [27, p. 26]. Scott was reputed to be quite good at golf and also showed interest in tennis. In 1883, she had the honor of presenting a silver challenge cup to the doubles champions of the much anticipated annual intercollegiate tennis match between Newnham and Girton.

In 1885, Scott migrated to America to become the first head of the mathematics department at Bryn Mawr College. As chair, a position she held for nearly forty years, she influenced and inspired many young students of mathematics and supervised seven doctoral dissertations. She worked in the field of algebraic geometry

²²Temperley was fifth wrangler in 1871 and Walker was second wrangler in 1879. Tragically, Walker drowned in 1883 soon after taking up the position of the first mathematics chair at Auckland University College [4, p. 132].

²³Sophia Bryant (née Willock), awarded her degree from the University of London in 1884, was the first woman to receive a DSc in England [22, p. 214].



Fig. 1.3 Tennis on Emily Davies Court, June 1908. Courtesy of the Mistress and Fellows, Girton College, Cambridge.

specializing in analyzing singularities of algebraic curves and on investigating properties of planar curves of degree higher than two. With Frank Morley, she co-edited the *American Journal of Mathematics*, founded by J.J. Sylvester at Johns Hopkins University in 1878. She published an advanced undergraduate geometry textbook and two dozen research articles, and presented a dozen papers at meetings of the American Mathematical Society, making her one of the most active American mathematicians at the turn of the century. Her work was widely recognized in Europe, as well as in America, and she had the distinction of being the only woman included in the first edition (1906) of Cattell's *American Men of Science*. Scott was an organizer of the College Entrance Examination Board and served as the Board's chief mathematical examiner. She was active in the American Mathematical Society, serving on its council and as a vice president. It was not until 1976 that another woman, Mary Gray of American University, served as a vice president of the AMS.

Scott persevered through a series of health issues. Her hearing, which had been noticeably poor even at Girton, progressively deteriorated and she suffered from acute rheumatoid arthritis. In addition, she had the misfortune to be struck by lightning in 1918. She carried on for several more years, retiring from Bryn Mawr in 1925. In retrospect, one cannot help but wonder what effect foreknowledge of Scott's influential mathematical career might have had against nineteenth-century claims that women were incapable of original mathematical thought.

Like Scott, **Sarah Marks**, Girton's other Mathematical Club founder, went on to embark on a fruitful research career. Born in 1854, Marks was the third child of a British seamstress and a Polish Jewish watchmaker who had emigrated to England. Her father died when she was seven, leaving behind a pregnant wife and seven children. At the age of nine, based on her intellectual acumen, Marks had the good fortune to live with and attend a school run by her aunts, thereby attaining access to the preparation necessary to be successful at Girton.

Marks came to Cambridge in 1878, the first Jewish woman to attend the university. During the last quarter of the nineteenth century, Marks became the most prolific of Girton's contributors to the *Educational Times*, responsible for submitting 3.5 percent of the solutions appearing between 1883 and 1889. Her performance on the 1881 Mathematical Tripos was at the level of third-class honors, disappointing given that she had done quite well on the Little-go, but perhaps not unexpected. Illness had delayed her studies by a year and Marks is reported to have described herself as "bad at examinations [24]," by which she may have meant that she had difficulty structuring her time wisely. A reminiscence by A.P. Trotter, a past president of the Institution of Electrical Engineers, suggests that she elaborated on some questions, but left no time for the others [41]. Concerns for the well-being of her mother and invalid sister may have been a further distraction [26].

After leaving Girton, Marks took on teaching work to help support her family. She spent a year teaching at Kensington High School before working as a private mathematics tutor for two years. In 1884, she began attending a physics course offered by Professor William Ayrton, FRS, at Finsbury Technical College. They were married in 1885. In addition to taking her husband's name, Marks changed her first name to Hertha. The name may have been suggested by a friend, likely Otilie Blind. Reputed origins for the nickname include comparisons to the Teutonic goddess Erda, the goddess of creation embodied in Swinburne's poem *Hertha*, and the heroine of the novel *Hertha* by Swedish feminist Fredrika Bremer.

Inspired by research that her husband had abandoned, Ayrton began experimenting with electric arcs, which were widely used for lighting at the time. Her research generated significant industrial and commercial interest, eventually leading to the production of more reliable searchlights and improvements in the performance of movie projectors. She became the acclaimed European expert of the electric arc and was commissioned to write a series of papers for *The Electrician* that formed the basis for her book, *The Electric Arc*. Ayrton was elected to full membership in the Institution of Electric Engineers in 1899, the first woman to achieve that distinction.

At the time of Ayrton's early successes, a growing number of women researchers were garnering recognition for their scientific work. The influence of women's colleges was tangible in the decades following 1880, as research from an increasing number of women authors found its way onto the pages of scholarly British journals such as *Nature*, *Proceedings of the London Mathematical Society*, and the prestigious *Philosophical Transactions* and *Proceedings of the Royal Society of London* [22, p. 177].

Although the Royal Society was not averse to women authors, membership was a different matter. The London Mathematical Society had elected its first

Fig. 1.4 Hertha Marks Ayrton (1854–1923). Courtesy of the Mistress and Fellows, Girton College, Cambridge.



female member, Charlotte Scott, in 1881. Yet, when Ayrton was nominated by John Perry for Fellowship in the Royal Society, with the support of several other co-signatories, as well as her husband, the opinion of counsel was that her certificate of candidature “... be not registered or read, on the ground that the candidate, being a married woman, is not qualified for election.” Counsel noted that eligibility of an unmarried woman was doubtful, adding that, “A woman, if elected, would become disqualified by marriage.”²⁴ It appears that the diminished legal status of a married woman, as dictated by common law, conflicted with the eligibility requirements of the Society’s charters and statutes. The Royal Society eventually opened its doors to women in 1945, 22 years after Ayrton’s death and 17 years after the Equal Franchise Act of 1928 granted equal voting rights to women and made clear a woman’s status as her own “person.”

After the publication of her book on electric arcs, Ayrton’s attention shifted to the intriguing wavelike motions and development of ripple marks on the sea floor (Figure 1.4). Her research into the phenomenon showed how sand ripple formation applied to coastal erosion and sandbank formation. An early article on this research, *The Origin and Growth of Ripple-Mark*, was read before the Royal Society in 1904,

²⁴Quotes from Royal Society Minutes of Council for 23 January 1902, reproduced in [26].

but publication in the *Proceedings* was postponed until 1910.²⁵ Ayrton was awarded the 1906 Royal Society Hughes Medal²⁶ for her original research on electric arcs and sand ripples. During her later years, she devoted much of her time to women's and social causes, and was an active member of the National Union of Women's Suffrage Societies.²⁷

Women with notable accomplishments, such as Scott and Marks/Ayrton, played a key role in establishing the credibility of women scholars in the public eye. No less important were the contributions of those alumni who, with somewhat less attention, went on to teach and mold future generations of young women.

Born in Oxfordshire, **Kate Knight Gale** matriculated at Girton in 1877 and, like her classmate Sarah Marks, achieved the equivalent of third-class honors on the 1881 Mathematical Tripos. As one of the previously mentioned “steamboat ladies,” she eventually took an external Bachelor's degree from Trinity College, Dublin. Serving for two years as assistant mistress at a private school in Brighton, she went on to spend three years as second mistress at St John's School in Worcester Park, and another nine years as headmistress at the Blackheath Centre School. Gale emigrated to South Africa in 1895 where she served as a mathematical mistress in Wynberg, before becoming co-owner and joint headmistress of the Milburn House School in Claremont near Cape Town, where she stayed for many years.

Margaret Theodora Meyer, born in Ireland, spent time in Italy before entering Girton in 1879, two years after Gale. Meyer submitted a variety of solutions to the *Educational Times* that exhibited a thorough knowledge of geometry, calculus, mechanics, and physics. She was bracketed with the top senior optime on the 1882 Mathematical Tripos, only just missing the cut-off for the wranglers. Like Gale, her first teaching position was as an assistant mistress, a position she held for three years at Notting Hill High School. She then took the opportunity to return to Girton where she served as a resident lecturer from 1888 to 1918, taking on the additional duty of Girton's Director of Studies in Mathematics from 1903 to 1918. She was described as an outstanding teacher who supported student interest in post-graduate research [11]. In 1907 Meyer was awarded a Master's degree from Trinity College, Dublin. During World War I, she conducted aeronautical research for the British government and continued working for the British Air Ministry after retiring from Girton. She was among the ten women elected as Fellows of the Royal Astronomical Society in 1916, the year in which the society first admitted women as official members.²⁸ In addition to her academic and research interests, Meyer was an avid mountaineer

²⁵A footnote to the article states, “Publication postponed by author's desire.”

²⁶The Hughes Medal, named after the Welsh-American scientist and musician David E. Hughes, is an annual award bestowed by the Royal Society in recognition of outstanding original research in the physical sciences, particularly in applications to energy such as electricity and magnetism.

²⁷Much of the information on Marks/Ayrton comes from [36].

²⁸Prior to 1916, the Royal Astronomical Society had conferred honorary memberships on only seven women since its founding in 1820. The first two honorary fellows, Mary Somerville and Caroline Herschel, had been elected in 1835, but the women were not permitted to attend meetings. [2]