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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Volume 10

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Editors
Janet L. Beery
Department of Mathematics
University of Redlands
Redlands, CA, USA

Sarah J. Greenwald
Department of Mathematics
Appalachian State University
Boone, NC, USA

Jacqueline A. Jensen-Vallin
Department of Mathematics
Lamar University
Beaumont, TX, USA

Maura B. Mast
Department of Mathematics
Fordham University
Bronx, NY, USA

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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 Niefield, 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, Niefield 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.

Redlands, CA, USA — Janet L. Beery
Boone, NC, USA — Sarah J. Greenwald
Beaumont, TX, USA — Jacqueline A. Jensen-Vallin
The Bronx, NY, USA — Maura B. Mast
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Contributors

Sylvia T. Bozeman Spelman College, Atlanta, GA, USA

Noel-Ann Bradshaw Old Royal Naval College, University of Greenwich, London, UK

Susan D'Agostino Southern New Hampshire University, Manchester, NH, USA

Sloan Evans Despeaux Western Carolina University, Cullowhee, NC, USA

Jacqueline M. Dewar Loyola Marymount University, Los Angeles, CA, USA

Della Dumbaugh University of Richmond, Richmond, VA, USA

Sue Geller Texas A&M University, College Station, TX, USA

Judy Green Marymount University, Arlington, VA, USA

Sarah J. Greenwald Department of Mathematics, Appalachian State University, Boone, NC, USA

Leon M. Hall Missouri University of Science and Technology, Rolla, MO, USA

Rhonda J. Hughes Bryn Mawr College, Bryn Mawr, PA, USA

Patti W. Hunter Westmont College, Santa Barbara, CA, USA

Emelie Agnes Kenney Siena College, Loudonville, NY, USA

Jeanne LaDuke DePaul University, Chicago, IL, USA

Jemma Lorenat Pitzer College, Claremont, CA, USA

Colin McLarty Case Western Reserve University, Cleveland, OH, USA

Shawnee L. McMurran California State University San Bernardino, San Bernardino, CA, USA

Margaret A.M. Murray Department of Rhetoric, University of Iowa, Iowa City, IA, USA

Luis Ortiz-Franco Chapman University, Orange, CA, USA

Katharine A. Ott Bates College, Lewiston, ME, USA

Karl Schaffer De Anza College, Cupertino, CA, USA

Joachim Schwermer Universität Wien, Wien, Austria

Amy Shell-Gellasch Eastern Michigan University, Ypsilanti, MI, USA

James J. Tattersall Providence College, Providence, RI, USA

Laura E. Turner Monmouth University, West Long Branch, NJ, USA

Erica N. Walker Teachers College, Columbia University, New York, NY, USA

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. McMurran 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]

S.L. McMurran (✉)
California State University San Bernardino, San Bernardino, CA, USA
e-mail: smcmurra@csusb.edu

J.J. Tattersall
Providence College, Providence, RI, USA
e-mail: tat@providence.edu

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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.

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

[2] Full 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

[3]The 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

[4]The 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.

[5]At 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.

[6]Schools 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].

[7] Delve 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 Townshend[8] 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

[8] Isabella 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.

[9] Successful 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

[10]The 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

[11] Algebra 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

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

[13] Warnings 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]."

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

[15] In 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 "steamboat 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 degrees[18] 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

[16]The 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.

[17]Established 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.

[18]Such 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.

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

[20]Data 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' Scholar[21] 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

[21]The 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 basics 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 England[23] 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

[22]Temperley 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].

[23]Sophia 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 Ottilie 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,

[24] Quotes 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 Medal[26] 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

[25] A footnote to the article states, "Publication postponed by author's desire."

[26] The 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.

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

[28] Prior 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]

and served for three years as president of the Ladies' Alpine Club. She died in a collision with a bus while cycling in 1924. In her will, she bequeathed £2000 to Girton College for the benefit of women mathematics students. [30]

Margaret Frances Evans was born in Nottingham and educated at Nottingham and Wimbledon High Schools before matriculating at Girton in 1886. Although nearly a decade had passed since Scott and Marks were students, Evans' contributions to the *Educational Times* continued their tradition. Evans' studies must have prepared her well. She put in a first-class performance on the 1889 Mathematical Tripos and was bracketed with the 27th wrangler. After leaving Girton, Evans took a position as Mathematical Mistress at St Leonards School, which had been founded in 1877 by the St Andrews School for Girls Company. The school's program took advantage of the talent coming from Girton. Its first mistress was Girton pioneer Lousia Lumsden. Her successor, Jane Frances Dove, under whom Evans served, had also come from Girton. Unlike the careers of Gale and Meyer, Evans' professional career was short-lived. She opted for a family life. In 1893 she married a solicitor, Rowland Beevor, with whom she raised five children.

Like Meyer, **Emily Perrin** chose a career path that included both teaching and research. Born in Manchester, Perrin matriculated at Girton in 1880, achieving first-class honors on the 1883 Mathematical Tripos. She taught for two years at Cheltenham Ladies' College before returning to Girton as a senior lecturer in mathematics. In 1888 she interrupted her career to nurse her invalid father and, after his death, applied her mathematical skills as a computer in Karl Pearson's statistical research laboratory at University College, London. While there, she studied properties of contingency tables and published several articles in Pearson's journal *Biometrika*.

Perrin was eventually joined by two other Girtonians, **Frances Evelyn Cave-Browne-Cave** and her older sister Beatrice, both of whom abridged their surname to Cave for professional work.[29] The sisters were educated at home in Streatham, London, before entering Girton in 1895. Frances excelled at mathematics and was bracketed with the fifth wrangler on the 1898 Mathematical Tripos, just behind G.H. Hardy.[30] In 1899, she was awarded the first research grant offered at Girton, a three-year research studentship funded by Florence Durham. Her research, directed by Pearson, resulted in two collaborative publications on barometric measurements that appeared in the *Proceedings of the Royal Society*. Although she continued to do limited work for Pearson in her spare time, Frances focused her energies on teaching. She remained at Girton as a lecturer from 1903 to 1936 and as Director of Studies from 1918 to 1936 (Figure 1.5). She received an external MA degree from Dublin's Trinity College in 1907 and a titular MA from Cambridge in 1926.

Like her sister, **Beatrice Mabel Cave-Browne-Cave** was very good at mathematics. She achieved second-class honors on the 1898 Mathematical Tripos.

[29] The composite surname had developed over centuries with marriage, land acquisition, and a baronetcy [13].

[30] Hardy had elected to take the exam one year early.

Fig. 1.5 Frances Evelyn Cave-Browne-Cave (1876–1965). Courtesy of the Mistress and Fellows, Girton College, Cambridge.

In the following year, Frances and Beatrice sat for the more challenging Part II of the Mathematical Tripos, passing at the first-class and third-class levels, respectively. Beatrice went on to teach for 11 years at a girls' high school in Clapham, filling some of her spare time with computing work at home. In 1903, the Cave sisters were among six collaborators who worked on a large study of child development, overseen by Pearson, that analyzed data collected from over 4000 children, including some of Beatrice's high school students [18]. Their part-time work for the Biometrics Lab was uncompensated until a grant established in 1904 by the Worshipful Company of Drapers allowed Pearson to provide his assistants with small stipends. In 1913, Beatrice went to work in Pearson's lab as a computer, coauthoring two papers that appeared in *Biometrika*.

Our final stories from the nineteenth century center on Isabel Maddison and her classmate Grace Chisholm, both of whom had the serendipitous opportunity to be among the first women to attend Göttingen and work with Felix Klein.

Born in Cumberland, England, in 1869, **Ada Isabel Maddison** (Figure 1.6) was the daughter of a civil servant. She had done her preparatory work at University College in Cardiff before coming to Girton in 1889 with a Clothworkers' Scholarship.[31]

[31]The Clothworkers' Company, founded in 1528, has a long history of involvement in charitable activity. In 1874, in response to a petition from nearly 50 women studying at Cambridge, the Clothworkers' Company established separate scholarships for Girton and Newnham in aid of higher education for women. In particular, the recommendation was to confine scholarships "...to ladies of scanty means, especially those engaged in, or preparing for, the profession of Education." Rationale included the long-term goal of raising the standard of female education generally and providing a supply of qualified educators. At Girton, women who excelled on the entrance exam, demonstrated need, and displayed dedication to teaching were eligible for the award. Girton scholarships were tenable for the three-year collegiate term. [10]

Fig. 1.6 Photographic portrait of Isabel Maddison as a child, Bristol, England, by photographer Davies Brothers, circa 1880s. Photo Archives, Special Collections Department, Bryn Mawr College Library.

Maddison achieved the level of first-class honors on the 1892 Mathematical Tripos and took an external BSc degree, with honors, from the University of London.

After completing her course of study at Girton, a fellowship presented Maddison with the opportunity to take up graduate studies at Bryn Mawr under Charlotte Scott's supervision. Scott encouraged Maddison to do research in the field of differential equations. Evidently, the subject was a good choice. In 1894, Maddison was awarded Girton's 1894 Gamble Prize[32] for her paper on differential equations that had appeared the previous year in the *Quarterly Journal of Pure and Applied Mathematics*. Meanwhile, Bryn Mawr's Mary E. Garrett European Fellowship for the year 1894-95 provided Maddison with a marvelous opportunity, a chance to take part in the vital mathematical community being cultivated by Felix Klein at the University of Göttingen. While there, Maddison participated in seminars and attended the lectures of Klein, David Hilbert, and Heinrich Burkhardt. After two semesters abroad, she returned to Bryn Mawr and, in 1896, completed her PhD

[32]Named after Jane Catherine Gamble, the prize was part of Girton's initiative to encourage post-graduate research. It was awarded annually to the best essay or dissertation by a certified student, with subjects rotating in a three-year cycle.

Fig. 1.7 Grace Chisholm Young (1868–1944). Courtesy of Sylvia Wiegand.

in mathematics with a thesis on differential equations and geometric invariants. Maddison spent the rest of her career at Bryn Mawr teaching mathematics and engaged in administrative duties as secretary, and then assistant, to President M. Carey Thomas. Although her duties left her little time for mathematical research, Maddison received recognition for her *Handbook of British, Continental and Canadian Universities*, which included useful information on foreign courses of study that were open to women graduates.[33]

While at Göttingen, Maddison met up with **Grace Emily Chisholm** (Figure 1.7), a close friend from Girton with similar accomplishments. In their 1891 year-end exams at Girton, Maddison was top of the second class with Chisholm just behind her. Although Maddison was disappointed in her own performance, Chisholm, who admired Maddison's intellect, felt accomplished at having come in so close to her friend. Both women had been present the previous year for the sensational announcement that Philippa Fawcett of Newnham had surpassed the senior wrangler on the Mathematical Tripos, Geoffrey Bennett of St John's College, by more than

[33]The handbook was initially compiled in 1896 for the Graduate Club of Bryn Mawr. For those students interested in study abroad, the handbook outlined the positions of foreign universities regarding the admission of women to degree programs and included brief descriptions of calendars, entrance requirements, and courses of study. An extended edition published in 1899 found that "...practically all European universities and colleges were open to women ... [25]."

thirteen percentage points.[34] Inspired by Fawcett's performance, Maddison and Chisholm aspired to, and achieved, first-class honors on the 1892 Mathematical Tripos with similar performances. Chisholm scored slightly above her classmate with a ranking between the 23rd and 24th wranglers, whereas Maddison tied with the 27th wrangler. The success of both women was likely due to the rigorous coaching of their tutor, William Henry Young. When Chisholm's previous coach, Arthur Berry, could not continue for her final year, she was urged to join Maddison who was being tutored by Young. Chisholm was apprehensive about engaging Young as he had a reputation for pushing his students ruthlessly and making his women students cry. Her opinion softened when she caught her first view of Young from the rooms of Frances Evans, then a first-year student with whom Chisholm had found an affinity and formed a lasting friendship. Unexpectedly, Chisholm was favorably impressed by the fine features and bright blue eyes of the man who would become her husband.[35]

Apparently, Chisholm and Maddison were not satisfied with a first-class performance on the Mathematical Tripos. On a dare, possibly from Chisholm's brother Hugh, she and Maddison also sat for the 1892 Oxford Mathematical Honour School examinations, where Maddison achieved the equivalent of a second, and Chisholm not only achieved a first, but is reported to have earned the highest mark for all students at Oxford that year. The results were not recorded because the arrangement was informal. The following year, Chisholm made an impression by successfully completing the more advanced Part II of the Mathematical Tripos.

The timing of Chisholm's strong performance at Girton could not have been better. Germany had begun to embrace a program that promoted women's education and Klein had been asked to look for promising foreign female students to invite to Göttingen. In 1893, the university opened its doors to women and Chisholm was among the first three women to be admitted. While there, in addition to studying physics and astronomy, she had the distinct opportunity to do mathematical research in the field of spherical geometry under Klein's supervision. With Klein's encouragement and support, Chisholm was awarded her doctorate in mathematics from Göttingen, magna cum laude, in 1895, thereby becoming the first woman to be awarded a German doctorate by completing all the necessary course work and defending her thesis.[36] Meanwhile, a romance developed between her and Young. When Chisholm married Young in 1896, she embarked on a life filled with family and mathematical research. While raising six children, she authored 18 papers, coauthored over a dozen papers and books with her husband, likely edited scores of her husband's research papers, and, following in the footsteps of Isabel Maddison, won the 1915 Gamble Prize for her essay on infinite derivatives.

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[34] The 1890 Mathematical Tripos taken by Fawcett was a 36-hour examination spread over six days that consisted of 140 problems, many with several parts.

[35] Much of the personal information in this paragraph and the next comes from [17].

[36] Sofia Kovalevskaya had set a precedent in 1874 by earning a mathematics doctorate from Göttingen *in absentia* that was based on her thesis and did not involve university coursework or an exam.

1.5 Research in a New Century

As the *fin de siècle* approached, Girton began to take on a new face to accompany the new century. Over 25 years, the student body had increased five-fold, growing from 23 students in the fall of 1875 to 115 in the fall of 1900. Additions to the college included a laboratory, the Stanley Library, the Hospital Wing, the Chapel Wing, and the College Hall. Whereas the campus was able to house 80 students in 1884, by 1902 it could accommodate 180. Moreover, the new housing gave many students two rooms of their own instead of one [7, p. 56].

The Mathematical Tripos, too, underwent significant change as the new century progressed (Figure 1.8). During the latter part of the nineteenth century, the exam had come under attack by Cambridge reformers seeking to modernize the exam. They argued that its competitive ranking system and dependence on memorization hindered original mathematical research and creative thought. Changes to the exam in the 1880s that had divided the exam into a more general Part I and the more specific Part II had been a start, but greater changes were being sought.[37] Ironically, some reformers used the success of women "wranglers" such as Scott and Fawcett to support their cause. They surmised that women could be capable followers, but lacked originality, and used that premise to advocate the argument that the success of women on the exam confirmed its rote nature and could only mean that the exam did not test propensity for creative mathematical thought. Given what this implies about the caliber of Cambridge's long line of male wranglers, such an argument was somewhat contentious. Nevertheless, the practice of publishing the comparative ranking of women with the Mathematical Tripos order of merit seems to be one of the factors leading to the gradual loss of prestige associated with the exam [22, p. 145–7]. Other more tangible factors included the growing popularity of the natural sciences tripos and a shift in focus from applied mathematics to pure mathematics [44, p. 276]. In 1909, through the efforts of Hardy and others, the Mathematical Tripos was reformed. The order of merit was abandoned in favor of an alphabetical listing of the honors candidates for each class.[38] In addition, the revised examination included more questions pertaining to pure mathematics rather than applied mathematics.

In the years leading up to World War I, Girton's undergraduate academic performance was somewhat less remarkable than that of its earlier years. Perhaps better preparation and changing attitudes regarding the tripos relieved some of the

[37] When Cambridge began to award degrees to women in 1948, the degrees of BSc and MA would finally be conferred for successful performances on Parts I and II of a tripos.

[38] In his 1926 Presidential Address to the Mathematical Association, Hardy defended his feeling that, "...the best thing that could happen to English mathematics, and to Cambridge mathematics in particular, would be that the Mathematical Tripos should be abolished." Hardy acknowledged that the glamour of the exam had faded, stating, "It is no longer true that the development of a decent school of English mathematics is being steadily throttled by the vices of its principal examination." Yet, he still felt that mathematical teaching at Cambridge and Oxford was hampered by the exam. [20]

Fig. 1.8 Girtonians leaving to take the tripos examinations in 1917. Courtesy of the Mistress and Fellows, Girton College, Cambridge.

onus of having to prove oneself. Compared to their forerunners, undergraduates spent less time focused on academic study while pursuing interests in athletics, clubs, and other social activities. Many women also participated in the women's suffrage movement. Although the Girton faculty was not always pleased by the new generation's decreased academic focus, one might find it heartening that these young women were able to enjoy a university experience more akin to that enjoyed by the men. Yet, worries were not unfounded. Even though students were making satisfactory progress, the possibility loomed that anything less than academic excellence might be used to suggest inferior performance [28, p. 119].

Auspiciously, post-graduate research at Girton began to blossom. Among Cambridge men, interest in post-graduate research had been on the rise since the 1880s. As women began to come to university better prepared, many graduates aspired to research opportunities similar to those available to their male counterparts. Since its opening, Girton had been endowed with a number of undergraduate scholarships. Opportunities for financial support for women's research began to appear in the late 1890s. By 1938, Girton offered nine studentships and six fellowships [40]. In particular, during the period from 1920 to 1940, the Yarrow Research Fellowship stimulated the scientific and mathematical careers of a number of remarkable recipients.

Alfred Yarrow was a noted philanthropist. Apprenticed at age 15 to a firm that constructed marine engines for naval vessels, Yarrow eventually established his own shipbuilding business and amassed a considerable fortune. In addition to support for hospitals and convalescent homes, Yarrow donated generously to educational and research endeavors.[39] His association with Girton began in 1913. With hard times having fallen upon the college, Girton held a £24,000 debt. After a visit to Girton, Yarrow arranged to pay (anonymously) half of the debt if the College could raise the remainder. Girton successfully rallied enough support to meet the challenge, enabling the College to establish two fellowships in addition to paying off its debt. In 1920, Girton again benefited from Yarrow's generosity when he bequeathed £10,000 to support fellowships in the mathematical, physical, and natural sciences, with the unusual stipulation that both the capital and interest be expended within 20 years.[40]

The first Yarrow Research Scientific Fellow at Girton was **Dorothy Maud Wrinch**. When Wrinch first went up to Girton in 1913, she relished the freedom offered by Girton. She played on the tennis team, joined societies for music, debate and literature, and became involved with the Mathematical Club, still in existence 35 years after its founding. Yet, even with a full social life, Wrinch did not neglect her studies. An impressive academic, at the end of her first year she boldly elected to sit for Part I of the 1914 Mathematical Tripos. She took a disappointing second.

The following fall, Wrinch returned to a Cambridge overshadowed by the onset of World War I. Early on, the feeling was that the war would not last long. As time passed, the effects of war were brought closer to home as food and heating fuel were rationed and the lists of casualties began to include increasing numbers of friends and loved ones. Yet, university life continued and women filled the lecture seats vacated by new soldiers.

Determined to become a mathematician, Wrinch redoubled her academic efforts in preparation for Part II of the Mathematical Tripos. Even with its reforms, the exam still served as a gateway to a mathematical career. For Wrinch, nothing less than a first-class performance would do. Two years later, in 1916, she achieved her goal. A scholarship to read for the morals tripos provided Wrinch with the means to stay on and study logic with her hero, Bertrand Russell. Her plans almost went awry when Russell's commitment to pacifism, which was shared by Wrinch, landed him in a bit of official hot water and his lectureship at Trinity was revoked. Russell moved to London, where Wrinch traveled once a week to join three other students for Russell's private seminars on the study of *Principia Mathematica*. The following year Wrinch obtained a grant to study set theory under Hardy's supervision, and with unofficial input from Russell. Wrinch won the 1918 Gamble Prize for her paper on transfinite types. Hardy, who had been asked by the prize committee to judge her paper, deemed it worthy of the prize, but not so good as Chisholm's paper that had won the prize in the previous round. [41]

[39] One of the Yarrow's more generous donations was that of £100,000 in 1923 to the Royal Society to be used to support distinguished men in research. Yarrow had been made a Fellow of the Royal Society the previous year.

[40] Much of the information on Yarrow comes from [3, p. 232].

[41] Senechal has written an interesting biography of Wrinch [33], from which much of the material provided here is based.

Wrinch took on a teaching position at University College London in 1918, earned a MS with distinction in 1920, and a DSc the following year. Meanwhile, she began working closely with the applied mathematician Harold Jeffreys, with whom she published several papers on probability theory and the scientific method. With the Yarrow Research Fellowship, awarded in 1920, Wrinch returned to Cambridge to do research and, while there, became the first woman in Cambridge history to teach mathematics to men. In the summer of 1922, she married her dissertation advisor John William Nicholson, fellow and director of studies in mathematics at Balliol College, Oxford. In 1923, with her fellowship completed, she joined her husband at Oxford with a teaching position that eventually evolved into the first university lectureship in mathematics to be held by a woman at Oxford, thereby opening her lectures up to male students. In 1929, she became the first woman to be awarded a DSc from Oxford. The previous year she had given birth to a daughter. The following year she divorced her husband. Determined to pursue her career, she found herself in the difficult role of a working single mother.

Meanwhile, Wrinch's research had turned to applications of mathematics in molecular biology. Her work on the fundamental structure of proteins led to international recognition and no small amount of controversy. When World War II broke out, she and her daughter emigrated to the relative safety of the United States. Wrinch remarried and accepted concurrent visiting professorships in molecular biology at Amherst, Smith, and Mount Holyoke Colleges, located close to one another in the Pioneer Valley of Western Massachusetts. She later accepted an appointment as a visiting professor in physics at Smith College.

Like many Girtonians before her, **Mary Taylor** benefited from the support of a Clothworkers' Scholarship when she came to Girton. She was bracketed in the first class on Part I the 1917 Mathematical Tripos and, in 1920, placed in the second class for Part II of the natural science tripos. She stayed on at Girton with research studentships and served as an assistant lecturer in mathematics from 1922 to 1924. During this time she developed an interest in the theory of radio waves, doing research under the direction of Edward Appleton of the Cavendish Laboratories. She continued her research at the University of Göttingen, where she was awarded her PhD in 1926. Her thesis focused on aspects of electromagnetic waves. The award of a Yarrow Research Fellowship allowed her to remain in Germany and study with Richard Courant.

Taylor returned to England in 1929 and served as a scientific officer at the Radio Research Station in Ditton Park.[42] She was the first woman to take up the study of radio as a profession. The civil service rules of the time compelled her to give up her position upon her marriage to Clive Slow in 1934. For several years she translated and abstracted papers for the *Wireless Engineer* and later taught mathematics at two local schools for girls. [19, p. 308]

[42]The station was under the supervision of the Radio Research Board, a component of the Department of Scientific and Industrial Research and of which Appleton had been a member. Work at Ditton Park in the late 1920s led to the discovery of the ionosphere.

Continuing the legacy of her mother, **Rosalind "Cecily" Young**, the eldest daughter and second child of mathematicians Grace Chisholm and William Henry Young, studied at the University of Lausanne obtaining her *Licenciés Sciences Mathématiques* in 1925 followed by post-graduate work at Girton under the direction of E.W. Hobson. She obtained her PhD under his supervision in 1929.[43] She was awarded a Yarrow Research Fellowship in 1929, and in 1939, like many of her predecessors, including her mother, was awarded the prestigious Gamble Prize for her essay on Schottky's Theorem. After a few notable publications in the early 1930s, including a paper coauthored by Norbert Wiener, she accepted a position in the Mathematics Department of Imperial College London. There she met Bernard Tanner, a maintenance engineer at the college, whom she married in 1953. Her subsequent publications in analysis and the history of mathematics carried her married name, R.C.H. Tanner. In the 1950s, her interest in inequalities led her to research and generate renewed interest in Renaissance mathematician Thomas Harriot.

The 1930s were highlighted by Yarrow Research Fellows Olga Taussky and Mary Cartwright, two promising young mathematicians who would each become quite renowned in their fields.

Olga Taussky, the daughter of an industrial chemist, was born in Olmütz, Austria-Hungary (now Olomouc in the Czech Republic). When she was young, her family moved to Vienna where she attended the Gymnasium. In 1930 she became the first woman to receive a doctorate from the University of Vienna. Her thesis on algebraic number theory was published in *Crelle's Journal* in 1932. Taussky worked as an assistant at Göttingen University before accepting a Yarrow Fellowship for the period 1934-37. The first year of her fellowship was spent at Bryn Mawr, the remainder at Girton. With help from Hardy, Taussky received a teaching appointment at Westfield College in London. In 1938 she married John (Jack) Todd, who was teaching at King's College London. The faculty of Westfield relocated to Oxford during the war. While there, Taussky-Todd supervised the DPhil thesis of Hanna Neumann, awarded in 1944. During the period 1943 to 1946, she worked as a mathematician at the National Physical Laboratory at Teddington. In 1947 she and her husband emigrated to the United States to work for the National Bureau of Standards. In 1957 they accepted positions at the California Institute of Technology, where Taussky-Todd became the first woman to teach at the school, the first to be tenured there, and the first to be promoted to full professor. In her career she supervised thirteen doctoral students and authored over 300 articles, making significant mathematical contributions to matrix theory and number theory.

[43]Under the titular statutes, women were eligible for doctoral degrees but not the franchise offered by a MA degree. In an attempt to attract American graduate students, Oxford began offering DPhil degrees in 1917; Cambridge followed suit just after World War I. Cambridge awarded its first PhD degree in mathematics in 1924. At the time, the PhD degree was regarded with some suspicion by British academics worried about its focus on specialized research as opposed to general scholarship.

Fig. 1.9 Mary Lucy Cartwright (1900–1998). Courtesy of the Mistress and Fellows, Girton College, Cambridge.

Mary Lucy Cartwright (Figure 1.9) did her undergraduate work at St Hugh's College in Oxford, where she was tutored by Dorothy Wrinch. Whereas Wrinch had found a hero in Russell, Cartwright's hero was Hardy. At Oxford, she found his undergraduate seminar to be of particular interest. In 1923, Cartwright achieved a first in mathematics at Oxford, becoming the university's first woman to achieve such a distinction. In recognition, St Hugh's awarded her their Hurry Prize. This annual prize, established in 1919 at the bequest of alumna Gladys Boyd Hurry, included an award of books given to the student who had demonstrated the best work in her studies during her university career.[44] After leaving Oxford, Cartwright taught for a time at the Alice Ottley School in Worcester and the Wycombe Abbey School in Buckinghamshire, but longed to return to her mathematical studies. She spoke with Hardy, who encouraged her to join his graduate seminar in the spring of 1928. The topic that term was summability.

Hoping to do research with Hardy, Cartwright's plan experienced a slight course change when Hardy exchanged jobs with Oswald Veblen of Princeton from October 1928 to May 1929. Although Cartwright attended Veblen's lectures, her main focus remained on analysis. Her supervision had been passed to E.C. Titchmarsh and,

[44]The Hurry Prize, now a monetary award, is still used to recognize St Hugh's most distinguished undergraduate.

even though he was only a year her senior, it was a good match. Hardy returned to England in 1930, resigning the Savilian chair at Oxford and accepting the Sadleirian Chair of Pure Mathematics at Cambridge. That same year Cartwright defended her DPhil thesis on the zeros of certain integral functions with Hardy as her advisor and Littlewood as one of the examiners.

In 1930, with the support of Hardy and Littlewood, Cartwright applied for and obtained a Yarrow Research Fellowship. She elected to undertake her research at Girton. During her first years at Cambridge, she occasionally wrote or spoke with Littlewood on topics pertaining to his courses. Eventually, the two mathematicians entered into a collaboration that spanned more than a decade. Cartwright's work with Littlewood on the van der Pol equation was among the earliest fully rigorous works on nonlinear oscillation theory. Their work motivated the development of dynamical systems and led to the development of radio, radar, and laser technology [37].

For many years, Cartwright was active in the Cambridge Women's Research Club. In 1947, she became the first female mathematician to be elected a Fellow of the Royal Society.[45] The following year she became Mistress of Girton College, where she provided leadership and vision for the students and staff for 19 years. She supervised nine doctoral dissertations, taking on students of both genders, and authored over a hundred articles. Even with her administrative duties, she continued her active involvement with the mathematical community, including a term of service as President of the London Mathematical Society from 1961 to 1963. She received the Sylvester Medal from the Royal Society in 1964 and the De Morgan Medal from the London Mathematical Society in 1968. The following year, Queen Elizabeth II recognized Cartwright's achievements with the title of Dame Commander of the British Empire.

While at Girton, Cartwright developed a close friendship with **Bertha Swirles**, who had held a Yarrow Research Fellowship from 1925 to 1927, just a few years before Cartwright. Swirles had attended the Northampton School for Girls before matriculating at Girton in 1921, where she, like so many before her, benefited from the generosity of the Clothworkers' Guild with a scholarship that supported her studies. She was awarded the Gertrude Mather Jackson Prize for Mathematics in 1923 and the Thérèse Montefiore Memorial Prize in 1924 for her first-class performance on the Mathematical Tripos.[46]

Swirles' interest in physics led her to follow the model set by her teacher, Mary Taylor, and try reading for the natural sciences tripos. When illness intervened, she decided not to complete the course of study [21], but to apply for funding to continue research with an eye toward a PhD. The Yarrow Fellowship followed by a one-year

[45]The Royal Society elected its first female Fellows in 1945.

[46]The Montefiore Memorial Prize was established in 1891 by Claude G. Montefiore to honor his wife who died in 1889 and had matriculated at Girton in 1882.

Hertha Ayrton Fellowship,[47] along with a two-year grant from the Department of Scientific and Industrial Research, allowed her to continue her studies. As part of her course of study, she was allowed to go abroad. Taylor, who had studied with Courant at Göttingen, encouraged Swirles to go there as well. During the winter and fall of 1927, Swirles took advantage of the opportunity to join Max Born's active physics community in Germany. After her return to Cambridge, she focused her attention on photoelectric effects and completed her thesis under the supervision of Ralph Fowler, receiving her PhD in 1929. Other doctoral students mentored by Fowler include Paul Dirac and Garrett Birkhoff. In 1938, after a series of teaching positions at the Universities of Manchester and Bristol, as well as Imperial College, Swirles became a lecturer in mathematics at Girton. Also, for a time, she was the director of studies in music. In 1940 she married Harold Jeffreys, of the Wrinch-Jeffreys collaboration, with whom she coauthored a popular textbook on mathematical physics.

1.6 Conclusion

Britain's colleges for women had a profound influence on women's education in the late nineteenth and early twentieth centuries. During the latter part of the nineteenth century, Girton and her sister colleges vastly improved the preparation of teachers, which in turn led to a marked improvement in secondary education for girls [28, p. 83]. As the cycle of better-educated teachers fostering better-educated students continued, young women began to reach for higher goals such as post-graduate research opportunities and university teaching. While British universities educated increasing numbers of women through the first half of the twentieth century, the accomplishments of their alumni continued to discredit suggestions that a woman's mind was any less suited for higher education, or creative research in mathematics, than a man's.

In our introduction we wondered if there was something special about their Cambridge experience that fostered the successful careers of so many Girton graduates. At Girton, women certainly benefited from the guidance of strong mentors, the tutoring and encouragement provided by sympathetic Cambridge men, the financial support of benefactors, and emotional support provided by each other. All contributed to their success.

In the period we have considered, women were gaining greater access to higher education not just at Cambridge, but also throughout Europe and America. Women from other colleges enjoyed successes comparable to those of their sisters at Girton. Evidence suggests that education itself provides a foundation for success. In retrospect, women cramming for the stagnant Mathematical Tripos had less access

[47] Funding for the Hertha Ayrton Fellowship came from an endowment for science established at Girton in 1925 by Ottilie Blind Hancock in memory of her friend Hertha.

to the horizon-broadening courses of study open to their sisters. So, one might say that they achieved success despite their Cambridge experience.

Perhaps it is necessary to expand the scope of the question. We can certainly make the case that there was something special about the women at Girton. Aware of the challenges to be faced, the women drawn to Girton necessarily embodied characteristics representative of agents of change in education: intelligence, determination, intellectual curiosity, persistence, a sense of purpose, altruism, and just plain pluck.

Looking at the bigger picture, these women achieved more than personal success; they helped reshape a culture. And it is here that, perhaps, the Cambridge experience played a special role. As we have seen, up until the early twentieth century, even among men, an honor's course of study culminating in success on a tripos, particularly the Mathematical Tripos, was the standard by which a Cambridge university graduate was measured and his future was gauged. Generation after generation of Girton alumni proved that women could meet that standard. If a woman could perform at the level of a man, and on his terms, should she not be entitled to the same opportunities? It would take more than successful performance on an exam to significantly alter society's perception of what a woman was and could be.

Through the stories of Girton's alumni, we see how women scholars influence a society's ideals. In girls' secondary schools, university-educated teachers empowered their students to aspire to higher education and prepared them for future success. In women's colleges, graduates who stayed on to teach provided valuable role models and encouraged new generations of undergraduates to further challenge boundaries in higher education. Women scholars who became renowned in their fields or engaged in scientific work shaped public opinion. Alumni who opted for family life were not only able to support the education of their own children, but also had the power to promote the benefits of education in their communities. Taken altogether, the diverse paths of women scholars challenged stereotypes.

Cambridge University can now boast of a fairly equitable gender mix in its undergraduate population.[48] As is the case with many research universities, the faculty ratio is much less encouraging, especially in mathematics. Of the 31 Cambridge colleges, none are all male and three are all female.[49] In 1976, Girton became the first Cambridge women's college to become coeducational. It is now one of the larger Cambridge colleges and admits a well-balanced gender mix. Girton's website depicts a community that continues the traditions of its founders with its commitment to "encourage excellence," "nurture potential," and promote "equality and inclusion." The twentieth century saw promising growth in Girton's contributions to mathematical and scientific communities. Incentives such as the Yarrow Research Fellowship encouraged women such as Dorothy Wrinch, Olga

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[48]From 2011 to 2015, the male:female acceptance ratio at University of Cambridge varied from 54:46 to 52:48 [42].

[49]The three women's colleges are Newnham, Lucy Cavendish, and Murray Edwards.

Taussky-Todd, and Mary Cartwright to successfully pursue careers as research mathematicians. We hope the trend this century will continue to lead toward a diverse and balanced mathematical community.

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Chapter 2
Pioneers: The Pre-1940 PhD's

Judy Green and Jeanne LaDuke

We dedicate this chapter to the memory of our dear friend Uta C. Merzbach, who mentored us both from the time we met in January 1978 until her death on June 27, 2017.

Abstract This chapter focuses on women in American mathematics during the century leading up to the founding of the AWM in 1971. In particular, it reviews results that appear in the authors' 2009 book *Pioneering Women in American Mathematics: The Pre-1940 PhD's* and in the supplementary material that can be found on the webpage http://www.ams.org/publications/authors/books/postpub/hmath-34-PioneeringWomen.pdf. To provide context for the understanding of women's early participation in American mathematics, we summarize the family backgrounds, education, and employment of the 228 women who earned doctorates before 1940. We provide details of the experiences and contributions of a number of these women.

Keywords American women • Education • Employment • PhD • Pioneers

2.1 Introduction

The Association for Women in Mathematics was founded in 1971. One hundred years earlier, Christine Ladd was twenty-three, had graduated from Vassar two years earlier, had taught at a town in central Pennsylvania for two years, and was about to take another teaching position. In 1882, Ladd *earned* the PhD degree in

J. Green (✉)
Marymount University, Arlington, VA, USA
e-mail: jgreen@marymount.edu

J. LaDuke
DePaul University, Chicago, IL, USA
e-mail: jladuke@depaul.edu

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mathematics, but the degree was not *awarded* until 1926, forty-four years later, when she was seventy-eight years old. Ladd thus bookends the authors' research: she was the first woman in our study to earn a PhD and the oldest to receive the degree. This study, published in 2009, covered 228 women who received PhD's in mathematics before 1940; this includes the 224 who received PhD's from US institutions and the 4 who were US-born and received foreign degrees [3]. Our goal was to present each of them, as fully as possible, from birth to death. Material supplementary to the book that includes extensive biographies and bibliographies of all the women in the study is available online [4].

In the late 1960s, when both authors were graduate students, very few women mathematicians were visible. Some made contributions, of course, but they were generally considered the exception. We assumed that what we were experiencing was the normal state of affairs. Indeed, during the 1950s only about 5% of the PhD's in mathematics were going to women. From the 1950s onwards the percentages grew slowly to 6% in the 1960s, to 10% in the 1970s, 16% in the 1980s, 23% in the 1990s, and since the early 2000s about 30% of the PhD's in mathematics have been awarded to women.

As a result of our study we learned that both the proportion and numbers of PhD's in mathematics going to women before 1940 were much higher than what we and others had previously assumed. Ten American women earned doctorates in mathematics before 1900, with the first such degree having been awarded in 1886. The remaining 218 who earned doctorates in the first four decades of the twentieth century comprise about 14.3% of the mathematics PhD's granted to Americans in that period. This proportion is slightly higher than that earned by women in all fields in the US at that time. It was not attained again by women in mathematics until the early 1980s.

2.2 Nineteenth-Century Background

The first PhD's awarded in the United States were granted by Yale in 1861; the first of these listed as a degree in mathematics was granted to John Hunter Worrall in 1862. Also in 1862 the first foreign mathematics graduate degree was awarded to an American when the university at Jena in Germany granted William Watson, later of Harvard, a PhD. The next two PhD's in mathematics were awarded in 1872 and 1873 by Cornell and Harvard, respectively.

The Russian Sonya Kovalevskaya is generally considered to be the first woman to receive a doctorate in mathematics in modern times. She studied privately at Göttingen in Germany as she had not been allowed to attend lectures there but was awarded the degree by Göttingen in 1874. Two years later Johns Hopkins University opened with an emphasis on graduate work, but it was not open to women. Christine Ladd studied informally at Johns Hopkins from 1878 until 1882 and did the work required to earn a PhD in mathematics, but the trustees refused to award the degree.

Much happened concerning graduate education for women between 1870, when there were already substantial opportunities for women to obtain a solid

Table 2.1 Nineteenth-Century Women PhD's in Mathematics

	Baccalaureate		Doctorate	
Winifred Edgerton* Merrill	1883	Wellesley	1886	Columbia
Ida Martha Metcalf	1886	Boston U	1893	Cornell
Annie MacKinnon* Fitch	1889	Kansas	1894	Cornell
Ruth Gentry	1890	Michigan	1894	Bryn Mawr
Charlotte Barnum	1881	Vassar	1895	Yale
Agnes Baxter* Hill†	1891	Dalhousie	1895	Cornell
Isabel Maddison‡	1893	London	1896	Bryn Mawr
Elizabeth Dickerman	1894	Smith	1896	Yale
Mary Winston* Newson	1889	Wisconsin	1897	Göttingen
Leona May Peirce	1886	Smith	1899	Yale
Anne Bosworth* Focke	1890	Wellesley	1900	Göttingen

*Surname at the time of the PhD degree.
†Born in Canada.
‡Born in England.

undergraduate education in the US, and the end of the nineteenth century. About 230 doctorates were awarded to women in the nineteenth century; of these about 50 were in the natural sciences and mathematics. The leading schools giving doctorates to women in mathematics and the natural sciences were Yale, the University of Pennsylvania, Cornell, Chicago, and Bryn Mawr College. Bryn Mawr had opened as a college for women with a graduate program in 1885, and the University of Chicago opened as a coeducational institution in 1892. Both were important for women doing graduate work in mathematics.

All but 2 of the 11 women listed in Table 2.1 as having received a PhD in mathematics in the nineteenth century were from eastern universities. Those two PhD's were granted to US-born women by Göttingen. Mary Winston was one of the first three women admitted to Göttingen, the first German university to admit women, although only for graduate work.

Another two of the nine US-born women listed in Table 2.1 had done post-baccalaureate studies in Europe: Ruth Gentry attended classes at the University of Berlin and the Sorbonne; and Leona May Peirce studied at Newnham College, Cambridge.

2.3 Family Background

The families in which the 228 women grew up represent a broad range of geographic, educational, and economic backgrounds. There were not diverse ethnic backgrounds, however. The group includes one Asian, Shu Ting Liu Hsia (PhD Michigan 1930), but no other racial minorities. It was 1943 before the first African-American woman received a PhD in mathematics; Euphemia Lofton Haynes earned her doctorate from Catholic University 29 years after having graduated from Smith College.

All but 16 of the women in our study were born in the US. The two leading states were New York (33) and Illinois (20). Both produced considerably more women than was to be expected from the population distribution in the country at the time. Apparently this reflected better than average opportunities for both undergraduate and graduate study in these states.

In general, the women in our study did not come from homes where the parents were highly educated or well off. Of those whose parents' occupations we were able to identify using census categories, just less than three quarters are divided more or less equally among the three categories: farmers, professional, and managers, while just over a quarter are made up of the combined categories of sales, service, craftsmen, clerical, and operators.

One rather extraordinary example is Gertrude Haseman (PhD Bryn Mawr 1917), who was born in 1889. Haseman was the seventh of nine children of an Indiana farm family and her mother greatly stressed the value of obtaining an education. All nine children received AB's, eight received master's degrees, and five earned PhD's.

Although few of our women came from homes where the parents were highly educated, some of these exceptions are notable. Six of the fathers earned PhD's at some point; two of these were in mathematics. Dorothy (Manning) Smiley Little (PhD Stanford 1937) was the daughter of W. A. Manning (PhD Stanford 1904); her father taught at Stanford and was her dissertation advisor. Frances Baker (PhD Chicago 1934) was the daughter of R. P. Baker (PhD Chicago 1910); her father taught at the University of Iowa.

2.4 Education

2.4.1 Undergraduate Education

The 228 women in our study did their undergraduate work at more than 100 different institutions including state universities and both large and small private colleges in the US and 8 foreign institutions. Two hundred and sixteen of the women in our study did their undergraduate work at US institutions, seven received their undergraduate degrees in Canada, and five received their pre-graduate training in Europe.

Just over half of the women attended coeducational schools and the rest single sex or coordinate colleges. The older women in our study were more likely to attend women's colleges since through the early 1900s women's colleges educated a large proportion of all college-educated women. In fact, for the women in our study, eight of the ten leading undergraduate institutions were all women's colleges in the East as shown in Table 2.2.

Table 2.2 Leading Baccalaureate Institutions

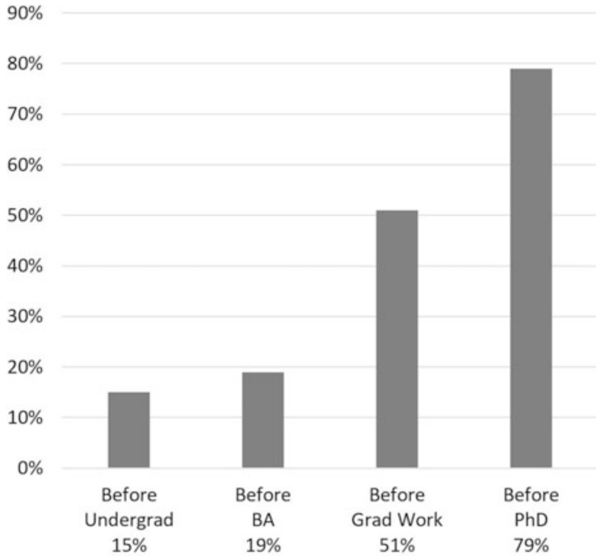
Institution	Number of Graduates
Wellesley	17
Goucher	10
Hunter	9
Mount Holyoke	8
Vassar	7
Smith	7
Brown (Women’s College)	6
Kansas	6
Wisconsin	6
Bryn Mawr	5

Wellesley College granted the most undergraduate degrees to women in our study. It opened in 1875 with a strong emphasis on mathematics and science. It was large and enrolled about 250 women when it opened. In the late 1880s and early 1890s it enrolled between about 650 and 800 women, more women than any other college in the country. During that period Helen Shafer, who had come to Wellesley as professor of mathematics in 1877, served as president of the college. Of the 17 women who graduated from Wellesley, more than half graduated by 1909. Nonetheless, the Wellesley mathematics department remained large, with between six and nine teaching faculty from the late 1890s until the late 1920s. Furthermore, with rare exceptions the department employed only women before World War II, and the faculty participated actively in the affairs of the larger mathematical community.

Goucher College in Baltimore was roughly a third the size of Wellesley and rarely had a mathematics faculty of more than two. Clara L. Bacon (PhD Johns Hopkins 1911) and Florence P. Lewis (PhD Johns Hopkins 1913) were on the Goucher faculty 1897–1934 and 1908–1947, respectively; they were the first women to receive PhD’s in mathematics from Johns Hopkins after graduate courses there were officially opened to women in 1907. Goucher’s close ties with Johns Hopkins were of great significance for the unusual success of its undergraduate mathematics program.

Hunter College was unlike either Wellesley or Goucher. It was a tuition-free, publicly funded, women’s college with no dormitories. In 1914 it changed its name from Normal College of the City of New York to Hunter College of the City of New York and by 1916 was the largest women’s college in the US. All but one of the nine undergraduate degrees granted by Hunter to these women was granted during the 1920s and 1930s when it was the leading undergraduate institution for the women in our study.

Fig. 2.1 Percent Employed Before PhD



2.4.2 Graduate Education

The two principal faculty members at Goucher, Clara L. Bacon and Florence P. Lewis, did not go directly from college to graduate school. As can be seen in Figure 2.1, this is true of most of the women in our study. We also see that about fifteen percent were employed before beginning college and nineteen percent before earning the bachelor's degree.

These numbers suggest that perhaps the motivation for obtaining the PhD for many (as was likely the case for many men at the time) was to become credentialed for college or university teaching. In fact, for almost all of the Catholic sisters who received PhD's from Catholic University in the 1930s, it appears that the degree was obtained in order to upgrade the level of instruction in Catholic women's colleges, many of which were just emerging as full four-year colleges from pre-existing academies in the 1930s.

The 228 women in our study received their PhD's from 37 different institutions (34 US and 3 foreign). Only one of these, Bryn Mawr, was a women's college and it is the only school that was both a leading baccalaureate and a leading doctoral institution.

One of the reasons that the University of Chicago was the largest granter of mathematics PhD's during the first four decades of the twentieth century (see Table 2.3) was its active summer quarter that brought in outside faculty and allowed graduate students with full-time jobs an opportunity to study while earning a living. Indeed, this summer session encouraged both men and women who were already fully employed to begin or continue with their graduate program. Another reason

Table 2.3 Leading Doctoral Institutions

Institution	Number of Graduates
Chicago	46
Cornell	21
Bryn Mawr	19
Catholic	14
Yale	13
Illinois	12
Johns Hopkins	12
Radcliffe	9
Columbia	8

was the attitude of acceptance of women, particularly by L. E. Dickson and G. A. Bliss.

This acceptance of women as dissertation students by highly regarded mathematicians was also important at other schools. Of the 100 degrees conferred by the top 4 institutions, 70 were directed by just 6 advisors: Dickson (18) and Bliss (12) at Chicago, Virgil Snyder (14) at Cornell, Aubrey Landry (13) at Catholic, and Charlotte A. Scott (7) and Anna Pell Wheeler (6) at Bryn Mawr.

2.5 Employment

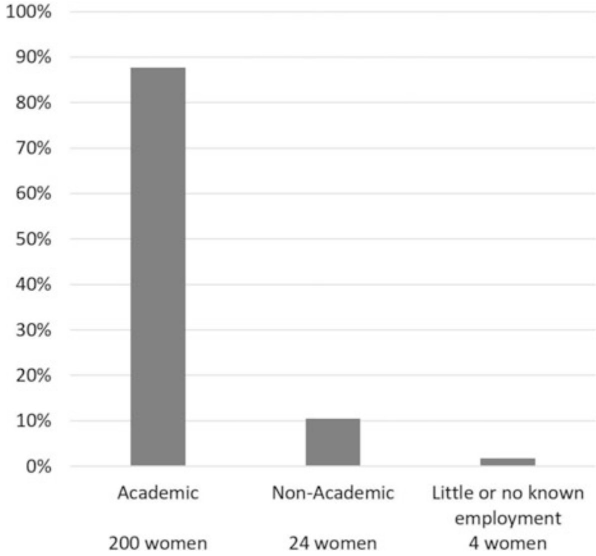
After receiving their doctorates, the 228 women in our study had nearly 600 different jobs at more than 300 different institutions: academic, government, and business. As indicated in Figure 2.2, by far the largest employers were academic institutions.

In order to determine the type of employment for each of the women, we counted the job in which that woman worked the longest.

2.5.1 Women in Academia

Eight of the top ten leading employers of the women in our study were women's colleges in the East; Hunter College in New York led the list having hired nine women. Eight of these nine women were hired between 1925 and 1931 and stayed on the Hunter faculty for at least 30 years. Wellesley followed Hunter as an employer. Seven women held their main positions at Wellesley with all serving at least 25 years. All but one retired as professor emeritus. The University of Illinois (Urbana-Champaign) was the third largest employer. Illinois employed sixteen of the women in our group at various times, but most were very short term, with only four of these being employed for at least 20 years and all four retiring at the rank of associate professor.

Fig. 2.2 Type of Employment



Most of the women in our study obtained academic positions at undergraduate institutions with an emphasis on teaching; they were about evenly divided between women's colleges and coed colleges or universities. More women (106) had their primary employment at coeducational institutions than at women's colleges (79), but those who taught at women's colleges had longer, more stable careers. At the women's colleges, the mean length of job was just over 30 years, whereas it was 21.5 years at coeducational schools. Overall, the smaller liberal arts colleges were generally the most supportive of women's careers.

On the other hand, institutions that had granted PhD's to the women were generally the least supportive. Just 17 of these 34 US institutions hired and retained a total of 24 of the women PhD's in faculty positions above instructor. Once employed, only 5 of the 24 ever attained the rank of professor before retirement and 2 of these 5 were at Bryn Mawr. Perhaps the most shocking situation was that of Florence Allen (PhD Wisconsin 1907) who served as instructor at Wisconsin for 43 years before being promoted to assistant professor two years before her retirement. In about 1980 a Wisconsin graduate remarked to one of the authors that she had not been aware that Florence Allen had a doctorate since, as an instructor, she was always called "Miss Allen."

Obtaining employment after receiving the doctorate was challenging for many women. The Great Depression, bias against women, and anti-nepotism practices were common barriers. The Great Depression affected nearly everyone—male or female. However, the women religious (Catholic sisters) seem to have met fewer impediments than other women in our study. One particularly striking description of the impact of the Depression was given by Elsie McFarland Buck (PhD California, Berkeley, 1920) in response to a questionnaire collected by the Smithsonian Institution in 1980.[1]

> I was teaching and semi-starving at a very small college in Spokane,.... At any rate, we were not getting paid very much money. I [taught] my whole nine months there for $360 and a box of apples and some kitchen cleanser donated by one of the students as part of his tuition. And I was sending out something like 300 or 400 letters of application all over the country. This was in 1932... when jobs were very few and far between [2, catalog number 2006.3037.01].

The contemporary writings of department chairs describe various views about hiring women before, during, and after the Depression. In 1920 R. D. Bohannan, chairman of the department at Ohio State, wrote R. G. D. Richardson, chair of the department at Brown, with regard to hiring two women students from Brown that "Our dean (Math is in Engineering College) does not like girls. We have two girl teachers.[2] Don't think we could get him to agree on another" [8]. In February 1924 R. G. D. Richardson wrote a recommendation for thirty-year-old Marian Torrey (PhD Cornell 1924) for a position at Smith:

> The department feels that we have never had, among the twenty or more girls whom we have sent out to teach in colleges, any stronger candidate. ... If Brown University would employ women, I would not hesitate to ask President Faunce to call her here at a good salary. She would do much better than many of the men whom we have at present on our staff [8].

In 1931 F. W. Owens, chairman of the department at Penn State and husband of Helen Owens (PhD Cornell 1910), wrote to H. S. Everett about hiring Chicago students: "We have an opening for an instructor for next year to supply for a man on leave of absence. ... For this position we would prefer a Gentile and a man. While we have both Jews and women on our staff, we can not have too large a proportion of them" [6].

As hard as it was for unmarried women to get jobs, the prospects for married women were even worse. It was often the case that women's colleges did not hire married women. For example, when Wellesley opened, it was understood that if a woman on the faculty married, she was expected to resign. An exception to this view on employing women who married was held by the president of Hunter College who indicated shortly after his inauguration in 1929 that when a woman married "the only thing such a person had to do was file her married name for payroll purposes" [7, p. 127].

Only 84 (37%) of the women in our study were married at some point in their life. Of those, 30 had little or no employment, 37 had significant interruptions in

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[1] Questionnaires and other documents concerning women in our study can be found in [2]. Some items relating to women mathematicians in the mathematics collection of the Smithsonian's National Museum of American History are described online at [10].

[2] One of the "girl teachers" was then 44 years old and had received her PhD in 1909.

their careers,[3] 10 had nearly continuous careers,[4] and only 7 had continuous careers; for 4 of these 7 the marriage was not relevant.[5] The husbands of 52 of the married women had, or would get, PhD's: 34 in mathematics and 18 in other fields. For these women, implicit and explicit anti-nepotism rules often affected their careers.

Anti-nepotism practices varied from institution to institution and at different times. For example, when in 1900 Mary Winston (PhD Göttingen 1897) married Henry Newson, a mathematics faculty member at the University of Kansas, she was not permitted to join the full-time faculty but was allowed to teach in the summers. After her husband died suddenly in 1910, the Kansas mathematics department hired Marion Ballantyne White (Chicago PhD 1910) but could not hire Winston Newson because her sister Alice Winston had just accepted an appointment in the English department.

In 1931 Elizabeth Stafford (PhD Wisconsin 1930) was hired as an instructor at Wisconsin. In June 1931 she married fellow mathematician Ivan Sokolnikoff. Elizabeth and Ivan Sokolnikoff both kept their positions at Wisconsin despite a university policy that prohibited married partners from holding faculty positions. In 1932 at the end of her first year of teaching and marriage, the chair of the department wrote to the dean that "… although Mrs. Sokolnikoff is one of our best instructors and is better prepared than any other instructor to give advanced work, we have omitted her from the tentative budget for next year due to the fact that you do not feel it wise to retain the wife of a member of the Department on the staff" [1]. Until they divorced in 1947, Elizabeth Sokolnikoff either held no position or was a lecturer. That year she was appointed an assistant professor.

An explicit instance of losing a job because of anti-nepotism policy occurred in 1948. In 1936 Emily Chandler Pixley (PhD Chicago 1931) was hired by Wayne University where her husband Henry Pixley was an assistant professor of mathematics. She was a special instructor and was paid an hourly salary. In 1947 her position was changed to a full-time position as a "regular substitute assistant professor." The following April, in a memo with subject "the university policy relative to employment of man and wife," the chair of the department wrote to the dean of administration that "… while the quality of teaching will be lowered somewhat by making Mrs. [X] and Mrs. Pixley the first to go, university policy demands that this be done, and I have already made clear to those affected that this will require the termination of their services in June 1949" [9].

Whereas it was understood that married women might well have family demands, some unmarried women also had family obligations that greatly affected their careers. For example, Elizabeth Cowley (PhD Columbia 1908) resigned her position at Vassar in 1929 and moved to Pittsburgh to care for her mother. After she resigned, Cowley became a high school teacher and changed the emphasis of her

[3]These interruptions were frequent, but not always, because of family responsibilities.

[4]For some, but not all of these women, marriage affected their professional situation adversely.

[5]Mayme Logsdon was a widow when she got her doctorate, Grace Murray Hopper was divorced early in her career, and Evelyn Wiggin Casner and Mina Rees did not marry until they were in their 50s when their careers were well established.

contributions. While on the faculty at Vassar she served on the council of the MAA[6] and reviewed two dozen books, most in French, German, Italian, or Spanish, for the *Bulletin* of the AMS; while teaching high school she was active in local and state mathematics educational organizations and wrote several articles on education.

As we saw earlier, few of the women in academia had positions that supported an active research agenda. Thus, while it is difficult to measure and describe the contributions of women whose primary task was teaching, we know that many were active in professional organizations related to mathematics and mathematics education, contributed articles and reviews to various journals, wrote books, and gave presentations at mathematics meetings. For instance, Clara E. Smith (PhD Yale 1904) served on the Board of Trustees of both the AMS and the MAA in the 1920s, was a vice president of the MAA, and co-wrote three textbooks.

Another woman in our study, Sister M. Helen Sullivan (PhD Catholic 1934), was very active in Kappa Mu Epsilon, the mathematics honor society for schools emphasizing undergraduate education that was founded by Kathryn Wyant (PhD Missouri 1929) in 1931; Sullivan served as KME's national historian and on the editorial board of its journal, *Pentagon*. She also participated in many NSF programs, e.g., as an NSF visiting lecturer and as part of the NSF sponsored College Geometry project at the University of Minnesota.

The leading producer of research papers in pure mathematics was Olive C. Hazlett (PhD Chicago 1915), who produced fifteen between 1914 and 1930, during her time at Chicago, Bryn Mawr, Mount Holyoke, and the University of Illinois. Lois Griffiths (PhD Chicago 1927) followed with thirteen, all but one while on the faculty at Northwestern University.

2.5.2 Non-academic Employment

As noted in Figure 2.2, only 24, about ten percent, of the women in our study had non-academic careers. While many were employed in the private sector, starting in the late 1930s the US government became a significant employer of these women. Four of those employed at some point by the government were particularly recognized.

Mina Rees (PhD Chicago 1931) received the President's Certificate of Merit in 1948 for her work during World War II on the Applied Mathematics Panel of the National Defense Research Committee (1943–1946). Although she continued working for the government at the Office of Naval Research until 1953, she spent most of her career at Hunter College and the Graduate School of the City University of New York, where the library now bears her name.

[6]The MAA Council changed its name to the Board of Trustees in 1920 while Cowley was a member.

Beatrice Aitchison (PhD Johns Hopkins 1933), who worked for the Interstate Commerce Commission, the Department of Commerce, and the US Post Office, received one of the first Federal Woman's Awards given in 1961 for her work especially as a transportation economist. Her government career was made possible by her having studied economics (MA Oregon 1937) during the Depression when jobs were hard to come by.

Grace Murray Hopper (PhD Yale 1934), who retired from the Navy with the rank of rear admiral, is known for her work in the then new field of computer science. She received the Legion of Merit in 1973, the Navy Distinguished Service Medal in 1986, and the National Medal of Technology in 1991. The USS *Hopper*, a guided missile destroyer, was named for her in 1996.

Gertrude Blanch (PhD Cornell 1935) started her career in the government working for the WPA-funded Mathematical Tables Project, was later employed by the National Bureau of Standards, and ended her career at the Wright-Patterson Air Force Base. She received the Air Force's Exceptional Service Award in 1963 and the Federal Woman's Award in 1964.

2.6 Conclusions

The 228 women in our study constituted a substantial community of women who came from rather ordinary backgrounds, who were well-educated at major research universities, and whose advisors were frequently among the most distinguished in their field. Most served as undergraduate teachers since they generally were not hired by research departments. Others, too, had rich and rewarding careers, both in and outside of academia.

The following quotations give us an idea of how some of the women in our study felt about being one of these pioneers. They are among the responses of 1,025 unnamed women who earned PhD's between 1877 and 1925 that appear in a dissertation by Emilie Hutchinson[7] [5, p. 23].

> Assistant Professor / College / Ph.D. 1915–1924... "Nothing but the most earnest conviction that she could never be satisfied without a Ph.D. in mathematics would justify a woman's setting herself that end. It is a long, hard road and when the degree is obtained, she finds that all the calls for mathematics teachers are for men, and that when a woman is employed in one of the large universities she is practically always given long hours and freshman work for years, with less pay than a man would receive for the same service. If all the women could fare as well as I have fared, I'd say 'Go ahead,' but alas! such unexpected good luck does not come to many in a generation" [5, pp. 185–186].

> Professor / College / Ph.D. 1915–1924... "No woman should attempt to get a Ph.D. unless she has very good health. She is likely to be a nervous wreck otherwise. It is a strain that can hardly be described" [5, p. 170].

[7] Of the 1,025 women questioned by Hutchinson, 371 had degrees in natural science or mathematics. Of the 371 nearly 40% were in chemistry

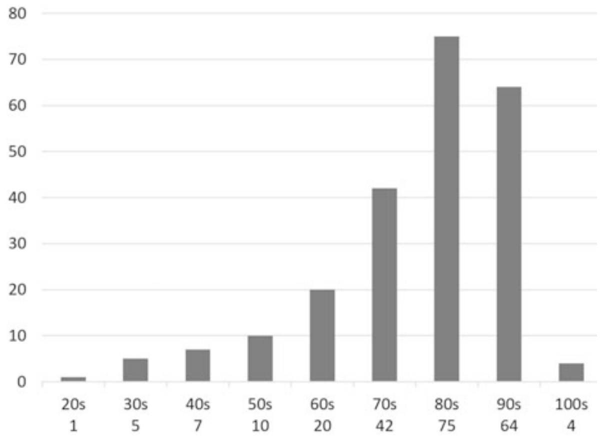

Fig. 2.3 Age at Death

> Professor / College / Ph.D. 1877–1915… "I did much more work than was required for the Ph.D. The freedom from monotony in the work in mathematics, the vision and grasp of fields of knowledge that may be interpreted through mathematics, the ideals of thought and of thinking, and the ability to interpret in conduct, relief from the turmoil of a crowded life,—all these make the Ph.D. more valuable than any professional advantage to be derived from it" [5, p. 173].

> Associate Professor / College / Ph.D. 1877–1915… "I should encourage women vigorously. My personal experience has been most fortunate. Apparently I have had only the knocks needed to act as spurs. I believe there is a better opportunity for women in the profession than ever before, let one be only willing to surmount difficulties and seek real achievement" [5, p. 101].

These comments are just four of the ten quotations from PhD's in mathematics in the Hutchinson paper and appear not to reflect differing responses based on the period.

The women in our study lived remarkably long lives, with a mean age at death of 80.8 and a median age at death of 84.7 (see Figure 2.3). This is, on average, more than eleven years longer than life expectancy tables indicate. In 2009 Rosella Kanarik (PhD Pittsburgh 1934) became the fourth centenarian among the women in our study. Kanarik, the oldest and last surviving woman, died in 2014 at age 105.

Finally, to expand on what appears above and to find more biographical and bibliographical information and sources used for all of these 228 women one can consult the nearly 700-page, freely accessible *Supplementary Material for Pioneering Women in American Mathematics* [4].

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Chapter 3
Käte Hey and Margaret Matchett—Two Women PhD Students of Emil Artin

Della Dumbaugh and Joachim Schwermer

Abstract The renowned mathematician Emil Artin supervised 31 doctoral students during his career, two of whom were women. His first doctoral student, Käte Hey, completed her PhD at the University of Hamburg in 1927, writing a thesis on the theory of zeta functions of simple algebras. Artin's second American PhD student, Margaret Matchett, worked with him at Indiana University, graduating in 1946. Matchett also studied zeta functions, redefining these functions with the help of the recently established concept of idèles attached to a number field. Both women conducted doctoral research on topics closely aligned with Artin's own celebrated work and quite relevant to the contemporary mathematics of the time. This chapter first provides some context for Artin's life and work, then explores the lives and the mathematics of Hey and Matchett. We conclude by contrasting the research accomplishments and career trajectories of Hey and Matchett with those of Mina Rees, who received her doctorate in 1931.

Keywords Emil Artin • Käte Hey • Margaret Matchett • Zeta functions

3.1 Introduction

That Emil Artin (1898–1962) acquired the nickname of "Ma" (short for mathematics) early in his career indicates how Artin was the physical embodiment of mathematics, embracing all aspects of the discipline that formed the center of his professional life. In his celebrated career, Artin oversaw the work of 31 PhD students, including two women: his first PhD student Käte Hey, at the University of Hamburg, and his second American PhD student Margaret Matchett, at Indiana University. After a short introduction to Emil Artin, this chapter explores the lives

D. Dumbaugh (✉)
University of Richmond, Richmond, VA, USA
e-mail: ddumbaugh@richmond.edu

J. Schwermer
Universität Wien, Wien, Austria
e-mail: Joachim.Schwermer@univie.ac.at

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of these two women, their mathematical research and interests, and their subsequent careers within the broader context of women in mathematics in the early- to mid-twentieth century.

3.2 Emil Artin

3.2.1 Artin's Early Mathematical Career in Germany

Born in *fin de siècle* Vienna in 1898 to an art dealer father and opera singer mother, Artin was influenced throughout his life by the rich cultural atmosphere of the late Habsburg Empire.[1] He was, as the algebraist Richard Brauer described him, as much artist as mathematician [13]. After his first semester at the University of Vienna in 1916, Artin was drafted into the Austrian Army, in which he served until the end of World War I. In 1919 he enrolled at the University of Leipzig and completed his doctorate under the direction of Gustav Herglotz in only two years.

Artin spent the academic year 1921–22 at the mathematically vibrant University of Göttingen. In October 1922, Artin gladly accepted an offer to come to the University of Hamburg as *Wissenschaftlicher Hilfsarbeiter* (assistant). The University of Hamburg, founded in 1919, had two chairs in mathematics, one held by Wilhelm Blaschke, the other by Erich Hecke. These distinguished scholars founded the international mathematics journal *Abhandlungen aus dem Mathematischen Seminar der Hamburgischen Universität*. This journal increased Hamburg's reputation as a mathematical center over the following years. One of the Artin's seminal manuscripts, "Über eine neue Art von L-Reihen" ("On a new kind of L-Series"), was published in this journal in 1924 [2].

Artin rapidly achieved academic promotions at the university and became full professor in October 1926. The next year, his first graduate student, Käte Hey, earned her PhD in mathematics. He remained in Hamburg until 1937 and his years there, especially the early years, were among the most productive in his life. During this time, he oversaw the work of 11 doctoral students, some of whom, such as Max Zorn, Harald Nehrkorn and Hans Zassenhaus, became well-known mathematicians. Artin's work in class field theory, the subject closest to his heart, led him to a solution of Hilbert's ninth problem, a proof of the most general law of reciprocity. The aim was to generalize Gauss's law of quadratic reciprocity and the higher reciprocity laws. Teiji Takagi's fundamental results on class field theory had appeared when Artin was a student [55, 56]. Using Takagi's theory, Nikolai Tchebotarev's 1922 proof of the density theorem (conjectured by Frobenius in 1880) [57], and his own theory of L-functions, Artin established his general law of reciprocity in 1927 [3]. Artin's theorem not only provided the final form of the classical question on reciprocity but it would become the central result of abelian

[1] For more on the culturally vibrant atmosphere in *fin de siècle* Vienna, see the quintessential source [53].

class field theory. Both Artin's result and his tools, particularly his L–functions, proved important—then and now—and his questions have guided research to the present day. Artin posed a conjecture about his L-functions that remains unanswered today [4]. His questions in non-abelian class field theory also remain open [23, pp. 13–14, 129].

In 1926–27, Artin and Otto Schreier developed the theory of formally real closed fields (fields with the property that -1 cannot be expressed as the sum of two squares; the field of real numbers is an example of a real closed field). This work laid the foundation for Artin's solution of Hilbert's seventeenth problem concerning how rational functions may be expressed as sums of quotients of squares. Artin extended Wedderburn's theory of algebras to non-commutative rings with chain conditions in 1928 [6] and the class of such rings is called Artinian in his honor.

3.2.2 Artin's Mathematical Career in the United States

Artin married one of his students, Natalie Jasny, in 1929. Given that she had at least one Jewish grandparent, the Nazis identified Natalie as Jewish. This designation and Artin's "sense of personal justice" compelled them to leave Germany and emigrate to America in 1937 [13, p. 28]. In the twilight hours of his term as President of the American Mathematical Society, Solomon Lefschetz had worked to secure a position for Artin at the University of Notre Dame. While there, Artin delivered a series of lectures in the mathematics department which subsequently formed the basis for his influential text on Galois Theory [8]. After a year in South Bend, IN, the young family moved about 200 miles southwest to Bloomington, Indiana where Artin assumed a permanent position at Indiana University.

At Indiana University, Artin taught the full breadth of the mathematics curriculum, including courses ranging from trigonometry to the graduate seminar, and oversaw the work of two PhD students, David Gilbarg and Margaret Matchett. Artin also began his collaboration with George Whaples, the newly minted PhD who had recently arrived at Indiana from the University of Wisconsin where Mark H. Ingraham, a student of E. H. Moore, had supervised his work. "The security of a permanent position at the University of Indiana combined with the structure of this teaching load to allow Artin to gradually resume his mathematical research" [22, p. 325].

Although between 1921 and 1931 "Artin's life had seen an activity not often equalled in the life of a mathematician," the next decade of his life was relatively quiet in terms of publications [13, p. 29] and from 1933 to 1940 Artin did not publish any research. As noted in [22, p. 325],

> The topics Artin suggested to his graduate students and his young collaborator, George Whaples, indicate that, although he had taken a bit of a hiatus from publishing mathematics, he had remained keenly aware of developments in his fields of interest. Artin, for example, was familiar with the new concept of idèles, introduced by Chevalley in 1936, and the critical turn that class field theory had taken as a consequence of this new approach; see

> [16, 17]. This global point of view provided the framework for Artin's fundamental work with George Whaples. In their joint work, they gave an axiomatic characterization of fields by the product formula for valuations. Together, they introduced the notion of valuation vectors, the additive counterpart of the idèles [10, 11].

In her 1946 dissertation *On the Zeta Function for Idèles,* Margaret Matchett continued the Artin and Whaples program [42].

Artin accepted a position at Princeton University in 1946, a move that seemed to revitalize his research activity. Originally hired as a Professor of Mathematics, Artin was awarded the Dod Professorship of Mathematics in 1948 and the Henry B. Fine Professorship of Mathematics in 1953. In this latter role, Artin succeeded two cornerstones in American mathematics, Lefschetz, who had held the Fine Professorship for the two previous decades, and Oswald Veblen, who had occupied the position from its inception in 1926 until his appointment as a Professor of Mathematics at the Institute for Advanced Study in 1932. Artin's promotion to this distinguished professorship underscored the respect he had earned from the department for his research accomplishments. Artin's response to his promotion to the Fine Chair provides a measure of his deep commitment to and love of teaching. As noted in [23, p. 51],

> When A. W. Tucker, then chair of the Princeton Department of Mathematics, informed Artin of his selection as the next Fine Chair of Mathematics, "[i]nstead of looking delighted, Artin looked concerned." Indeed, Artin initially declined the position because "the Fine Chair does no teaching. I will not give up my freshman calculus course and so I must respectfully decline the honor." Apparently Tucker consulted with university lawyers about the exact terms of the Fine endowment and they determined that voluntary teaching was permissible. With that issue resolved, Artin accepted the Fine Chair.

Artin's teaching prowess extended far beyond the freshmen, however. In his 13 years at Princeton, he oversaw the work of 18 doctoral students, including John Tate and Serge Lang [66]. He also resumed his work in the theory of braids, a topic that relates questions in group theory and topology. His prowess as a skillful expositor is everywhere evident in his "The Theory of Braids" that appeared in *American Scientist* in 1950 [9]. He remained at Princeton until March 1959, when he returned to Germany to take a position at the University of Hamburg. He remained in Hamburg for the rest of his life.

3.3 Käte Hey

3.3.1 Hey's Early Life and Education

Artin served on the faculty at the University of Hamburg for 15 years. Not long after Artin arrived at Hamburg, he took on his first graduate student, Käte Hey. Hey was born in Hamburg on February 19, 1904, as the daughter of Carl Hey and his wife Wilhemine (*née* Dupke). She attended school in Hamburg and graduated from the *Oberrealschule* (high school) in 1923, then enrolled at the University of Hamburg as a student in mathematics and physics. As one of her teachers, Artin directed her interests to number theory. As a result, Hey studied algebraic number theory, abstract ideal theory, and, in particular, in the non-commutative realm of algebra, the theory of hypercomplex number systems. Beyond the real or complex numbers, the notion of a system of hypercomplex numbers originated in the 19$^{\text{th}}$ century with the concepts of the quaternions and octonions and was later used as a general term for an associative algebra over some field [48]. In general, mathematicians studied hypercomplex number systems in order to gain insight into non-abelian class field theory.

3.3.2 Hey's Mathematical Research: Overview and Impact

Artin drew Hey into this topic when he suggested a thesis project for her which originated in the theory of zeta functions as developed by Dedekind for number fields. One of the main results in this classical theory is the proof of the functional equation for the zeta function of ideal classes in the ring of integers of algebraic number fields. Artin suggested that Hey extend this theory to the non-commutative case, that is, to establish the theory of zeta functions of hypercomplex number systems. In particular, Artin encouraged Hey to develop a theoretical framework for a suitable functional equation and its proof.

In December 1927, Hey completed her thesis *Analytische Zahlentheorie in Systemen hyperkomplexer Zahlen* [33]. This thesis contained quite remarkable results concerning not only the theory of zeta functions but also the geometry of the underlying fundamental domains originating with orders in hypercomplex number systems. In the final section of her thesis, Hey studied the special case of generalized quaternion algebras; that is, simple central algebras of dimension 4 defined over algebraic number fields and the orders therein. Hey's results in this case concern class number relations and unit groups of orders.

Although Hey's thesis was never published in a mathematical journal, it was printed in a version that met the usual university requirements. In his *Algebren*, Deuring included a survey of her results [21]. Artin's report [37] on this thesis indicates that he held Hey's work in high esteem:

> The transfer of the functional equation of the zeta function attached to ideal classes in algebraic number fields to ideal classes in hypercomplex number systems is an important and not a simple problem in the arithmetic of these systems.
>
> The difficulties lie in the fact that one only knows a few facts about the group of units and that the norm forms of the ideal classes are indecomposable so that the usual method of the decomposition into a product of Gamma integrals doesn't work.
>
> Both difficulties are resolved in the present work, and the author arrives at a functional equation of a type as simple as in algebraic number fields.
>
> Specializing the functional equation to quaternion systems leads to nice and very remarkable class number formulas which show that the investigation of these systems connects the theory of quadratic forms with many other areas of mathematics.

> The work was the topic of the prize call of the Faculty of Mathematics and Natural Sciences for the year 1927. I recommend the designation *sehr gut* ("very good") as suggestion. [Hamburg, 12/12/1927, Artin].[2]

Hey's thesis represented an astonishing piece of mathematical work for a young scholar. The sophisticated methods Hey used in her work made—and make—for difficult, technically demanding reading. As Max Zorn observed, however, Hey's thesis contained some mathematical inaccuracies and some gaps. Zorn corrected the mistakes [68] and made clear that the results obtained by methods in analytic number theory, combined with his corrections, already implied the local-global principle[3] for central simple algebras defined over some number field k. In the late 1920s and early 1930s, this was an important topic of research in arithmetic and algebra (see, for example, [5–7, 31, 45], and [46]).

Arnold Scholz reviewed Hey's thesis in the *Jahrbuch Über die Fortschritte der Mathematik* without mentioning these important consequences. In his review of Zorn's note [20], Max Deuring underscored the close relation, as displayed in Zorn's paper, between the results of Hey and the main theorem in the theory of central simple algebras over algebraic number fields, now usually called the Albert-Brauer-Hasse-Noether theorem. Not much later, Deuring exposed them in detail in his book *Algebren* [21]. Emmy Noether, who was in close contact with Artin, was well aware of the work of Hey and Zorn. It seems likely that Zorn's insight inspired Noether's suggestions for Ernst Witt's thesis topic dealing with class field theory in the function field case [67]. Beyond the German mathematical community, in Paris, for example, results in class field theory and the attempt to arrive at a meaningful non-abelian class field theory were discussed in the *Séminaire de Mathématiques*, run by Gaston Julia, in a year-long thematic cycle of lectures in 1933–34. In addition to talks by Andre Weil, Claude Chevalley, and Jean Dieudonne, in May 1934, Frèdèric Marty delivered a lecture, entitled "Les fonctions zeta dans les algèbres hypercomplexes" focusing on the results of Hey's thesis [12].

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[2] Authors' translation of: "Die Übertragung der Funktionalgleichung der Zetafunktion von Idealklassen in algebraischen Zahlkörpern auf Idealklassen in hyperkomplexen Zahlsystemen ist ein wichtiges und nicht einfaches Problem der Arithmetik dieser Systeme. Die Schwierigkeiten bestehen darin, dass man nur sehr wenig von der Gruppe der Einheiten weiss und dass die Normenformen der Idealklassen unzerlegbar sind, so dass der übliche Weg der Zerlegung in ein Produkt von Gamma-Integralen versagt. Beide Schwierigkeiten werden in vorliegender Arbeit überwunden und die Verfasserin gelangt zu einer Funktionalgleichung von ähnlich einfacher Bauart wie in algebraischen Zahlkörpern. Die Spezialisierungen der Funktionalgleichung auf Quaternionensysteme führt zu schönen und sehr merkwürdigen Klassenzahlformeln, die zeigen, dass die Untersuchung dieser Systeme die Theorie der quadratischen Formen mit vielen anderen Gebieten der Mathematik in Zusammenhang bringt. Die Arbeit war Preisaufgabe der math.–nat. Fakultät für das Jahr 1927. Ich bringe das Prädikat sehr gut in Vorschlag."

[3] This principle states that the isomorphism class of such an algebra A/k is determined by the "local" companions A_p defined over the local fields k_p, where p ranges over the primes of the underlying field k. This result, obtained in 1930 [14], is of fundamental significance in the arithmetic of division algebras. For the historical background see [51] and [26]. This important implication of Hey's work was apparently overlooked by Artin when he wrote his report.

Looking beyond Hey's thesis, her work fits into an impressive development in the history of mathematics. Following the new concept of the ring of adèles of an algebraic number field and the related group of idèles, Margaret Matchett, Artin's first and only woman doctoral student in America, took up questions related to the zeta function in her thesis (see Section 3.4.2). Ultimately, John Tate gave the classical theory of zeta functions a convincing new guise using methods from harmonic analysis in 1950 [15, 23]. In 1958, Fujisaki followed an argument similar to Tate's and mastered the technical issues in harmonic analysis arising out of the non-commutativity of the skew field to settle the non-commutative case successfully [27, pp. 69–70].

3.3.3 Hey's Later Life and Career

According to [58], Hey was very much interested in pursuing mathematics as an academic career. At the time, however, Hey's father felt obliged to financially support the education of Hey's two sisters, thus he directed her toward the teaching profession so she could earn her own living. She passed the state examination which qualified her to work as a teacher of mathematics and physics in secondary schools. On October 1, 1932, Hey married a colleague, E. Scheuer.[4] Shortly after her marriage, Hey stopped working as a school teacher and soon after she and Scheuer had four children. Hey passed away on July 23, 1990.

Hey's professional trajectory has to be viewed within the broader context of the time and culture in which she lived. The socio-economic status of Hey's parents did not allow them to support Hey independently as she pursued research mathematics. Thus, although Hey's thesis is still recognized as important work for the time, she was unable to pursue her research in number theory as a member of Artin's group in Hamburg or elsewhere, for that matter. It certainly was not a question of the topic of her research. The theory of hypercomplex number systems was a central issue in the 1930s, in particular, the arithmetic of hypercomplex number systems. Noether, in fact, would devote her 1932 International Congress of Mathematicians plenary lecture to this topic. Hey's decision to leave research mathematics may have been something more than a financial decision though. There were so few positions in mathematics available and even fewer occupied by women. Renate Tobies notes that there were only six women who completed a postdoctoral thesis (*Habilitationsschrift*) in Germany between 1913 and 1945. As Tobies put it, "[a]lthough each of these women produced outstanding research, they could not obtain a paid professorship unless they went into exile abroad (Noether and Geiringer), or persevered until after the end of the war" [60, p. 286]. In the group

[4]Scheuer's first name is unclear and is possibly Erwin. The authors would like to thank Renate Tobies [61] for this information, which came from a database of high school teachers at German schools in the 1930s.

of female graduates in Germany before 1937, only Noether, Hilda Geiringer, Ruth Moufang, Maria Pia Geppert, and Hel Braun held positions as professor and pursued mathematical research [58, p. 151].

3.4 Margaret Matchett

3.4.1 Matchett's Early Life and Education

Margaret Stump was born on April 21, 1918 in Rockford, Illinois.[5] Her parents Albert and Susan moved to Indianapolis shortly thereafter, where her father established a law practice. Matchett enrolled at Butler University, originally intending to study English in order to become a librarian. She was attracted to the logical precision of mathematics and decided to pursue studies in this area. Once she completed her undergraduate work at Butler, she began graduate work in mathematics at Indiana University (IU) in September 1938. Thus she and Artin arrived at IU at about the same time.

Matchett earned her master's degree in June 1939. She began work on a PhD that fall, taking many of her classes and all of her seminars from Artin [52]. During this time, she met Gerald (Jerry) Matchett when he came to IU as a new PhD to teach Economics. They married in 1942 and she set aside her graduate work to follow him as he pursued his career. As her son Andy Matchett later described it, Matchett "certainly wanted to get married and to this particular young man. However, I know she felt a sense of loss that she would have to give up her graduate studies" [39, p. 4].

Matchett followed her husband as he pursued his career as an economist with the War Relations Board, including to Colorado, where she assumed an instructor position in the Army Specialized Training Program (ASTP) at the University of Denver. She is also listed as an Instructor in Mathematics for the College Training of the Aircrew at the Air Force Base. The ASTP was a short-lived World War II program designed to train and educate talented enlisted men in engineering and languages [34]. G. Matchett taught Mathematics in this program [65]. Matchett made an effort to participate in the mathematics community during this time, delivering talks at sectional meetings of the Mathematical Association of America (MAA) [40, 41].

In March 1944, G. Matchett was drafted into the Army and Matchett "instantly zipped" back to Indiana University to resume her graduate work [39]. She finished her thesis *On the Zeta Function for Idèles* and was awarded her PhD in 1946. There was, then, in this particular case, a silver lining in an otherwise war-torn family.

[5]Much of the personal information contained in this section is drawn from [23]. That work relied, in part, on [39].

3.4.2 *Matchett's Mathematical Research: Overview and Impact*

In her thesis, Matchett approached analytic number theory by way of idèles and valuation vectors, now called adèles [42]. She redefined classical zeta functions using Claude Chevalley's new concept of the group of idèles attached to an algebraic number field K. This group carries the structure of a locally compact group so that measure theoretic methods could come into play. It was a decisive step in Matchett's work that she identified the characters of this group, the so-called idèle characters, as those characters of the ideal class group of the underlying field K which were introduced by Hecke in 1920 in his seminal work *Eine neue Art von Zetafunktionen* [32]. Less than five years later, after Artin moved to Princeton, his student John Tate would prove this last result in his 1950 thesis *Fourier Analysis in Number Fields and Hecke's Zeta Functions* [15]. Matchett never published her thesis, a fact that, according to her son, "annoyed" Artin [39].

Matchett was the only woman to earn a PhD in mathematics from Indiana University in the 1940s. Looking more broadly, she represented one of 44 women in the United States who received a PhD in Mathematics between 1945–1949. In that time period, those 44 women accounted for 9.3% of the total PhDs awarded in mathematics.[6]

In 1946, Matchett's husband came home from the war and assumed a position at the Illinois Institute of Technology (IIT) where she also secured an Instructorship. It seems Matchett still tried to remain involved in the broader mathematical community by having Dr. L. R. Ford present her paper on "Artin's treatment of the Gamma function" at the May 1947 meeting of the Illinois Section of the MAA [35, pp. 193–194]. It was unfortunate that Matchett was unable to attend in person. Karl Menger was in attendance, for example, and spoke on "Self-dual postulates in projective geometry" [35, p. 195].

Matchett taught mathematics at IIT until 1950 when her first child Andrew was born. A second child, Susan, was born in 1955. In the early and mid-1950s, Matchett devoted most of her time to raising her children, although she did work through mathematics books on occasion.

[6]By way of comparison, from 1940–1944, women earned 11.8% of America's PhDs in mathematics and from 1950–1954, women earned 4.8% of the PhDs [43, p. 5]. Indiana was not a school known for its large numbers of PhDs awarded to women in mathematics in the middle of the century. From 1940–1949, seven schools accounted for over half the PhDs awarded to women: Illinois (9), Catholic (8), Michigan (8), Radcliffe (7), Chicago (6), California/Berkeley (5), and Cornell (4) awarded 4 or more PhDs to women [43, p. 26].

3.4.3 The Communist Threat

Other less obvious factors must have influenced Matchett's personal and professional life at this time. The post-World War II era situated America and Russia as the two world superpowers and mistrust flourished between the two nations [25, p. 32]. American fears about communism escalated to epic proportions. The House Un-American Activities Committee (HUAC) had been founded in 1938 to investigate alleged disloyalties and subversive behavior by private citizens and/or organizations and was established as a permanent committee in 1945.[7] As Fariello aptly described it, "…the question 'Are you now or have you ever been a member of Communist Party?' served as a prologue to personal ruin, life in exile or on the blacklist, a shattered family, imprisonment, suicide, and for some even a violent death. For many who faced that question, the consequences of their answer still haunt them today" [25, p. 24].

Matchett and her husband came into the center of this dynamic when Herbert Fuchs identified them as members of the American Communist Party in his testimony before the HUAC [63].[8] Both Matchetts were subpoenaed by the HUAC to testify on December 14, 1955. In their testimony, they both cited their Fifth Amendment right to refrain from testifying against themselves.[9] Although Matchett and her husband were never charged or imprisoned, it must have been a difficult time for them.

3.4.4 The University of Chicago Lab School and New Math

In the late 1950s, Matchett began working part-time at the University of Chicago Lab School, associated with the University of Chicago.[10] Matchett's position soon became full-time and she eventually assumed the role of chair of the mathematics department there. While at the University of Chicago Lab School, for example, Matchett ensured that talented students would have an appropriately sophisticated

[7]For more on the evolution of this committee, sometimes referred to as the Dies Committee after its first chairman Martin Dies, Jr., see [47, chapter III].

[8]Fuchs testified before the House Un-American Activities Committee on Tuesday, May 15, 1956. Apparently, Fuchs worked with G. Matchett at the National War Labor Board in 1943–1944. See [63, p. 4074] for the reference to Fuchs' testimony and [63, pp. 4078, 4085–4086, 4094, 4097, and 4110–4103] for references to Gerald and/or Margaret Matchett. The authors extend their generous thanks to an anonymous referee of this paper for calling this source to our attention.

[9]Amendment V of the US Constitution reads: "No person …shall be compelled in any criminal case to be a witness against himself, nor be deprived of life, liberty, or property, without due process of law" [62]. See [64] for the Matchetts' testimony. For personal reminiscences by other university professors and teachers, see [25, pp. 426–446, 455–467].

[10]The Lab School is a private school founded as a progressive educational institution by John Dewey in 1896.

curriculum. She also collaborated with D. W. Snader on a text for elementary teachers titled *Modern Elementary Mathematics* [44]. The book is written in a style close to that of a workbook. The authors viewed this text as different "from an ordinary textbook" because "it can be used entirely independently. Thus the reader is given frequent opportunity to check whether he has understood, and to supply reasons, explanations, and next steps in a discussion" [44, p. vi].

This text on mathematics may have also been influenced by Matchett's work with the School Mathematics Study Group (SMSG) in the early 1960s. In the wake of Sputnik and, in particular, two National Science Foundation conferences on the improvement of mathematics education, the SMSG was founded in 1958 under the direction of Ed Begle, a topologist who had earned his PhD under the direction of Lefschetz in the 1940s and later shifted his research interests to mathematics education. SMSG was part of a national movement for curricular reform. The SMSG brought together research mathematicians with K–12 teachers to develop a new curriculum that emphasized concepts rather than computation. They were responsible for what was coined the "New Math" [49].

The first longitudinal study in the early 1960s showed mixed results for the work of the SMSG. Teachers, in particular, were frustrated with the effort necessary to learn new material and adopt new teaching methods [36, p. 30]. Matchett would not have been among these teachers who were frustrated because she had advanced training in mathematics, but, in general, that was not the case for others. As her son described it, "[i]t was very exciting [for her] to be among a group of topnotch educators trying to figure out how to develop mathematical thinking in children up through high school" [39, p. 9]. Although the new math may not have achieved the type of success the SMSG had hoped, Matchett had ample opportunity to consider pedagogical approaches, an apparent interest of hers, by working with this initiative. She was a favorite among the faculty at the Chicago Lab School, both for her strength and her compassion [19]. She retired in 1987 and died in 2002.

3.4.5 Matchett's Career in the Context of Trends for Women in the Workforce in the United States

Matchett's career followed broader trends in America, both in terms of the larger workforce and in terms of mathematics [43, pp. 35–37]. Claudia Goldin has outlined the progression of women in the workplace in the 20th century in her articles "Career and Family: College Women Look to the Past" and "The Quiet Revolution that Transformed Women's Employment, Education and Family" [28, 29]. Goldin argued that in the early 20th century, women had to choose between family or career. By mid-century, women often had marriage and children first, then pursued a career. In the 1960s and 1970s, women chose career and then family. Beginning in the 1980s women chose career and family. Goldin referred to the final stage of development, where women finally came to pursue career and family as a “quiet revolution” that necessarily followed the earlier “evolutionary” phases [29].

Consistent with broader trends in employment for women, Matchett had her children first and later she seemed to find her career at the Lab School. Here we use the term “career” to suggest that her identity was, in part, found in her occupation [29]. She was, as one colleague put it, “a great inspiration to her students and her colleagues, and a famous force for good in this neighborhood (Hyde Park).[11] Few people in Hyde Park were as well known, or as much loved, as she” [19].

3.5 In Comparison: Mina Rees, Käte Hey, and Margaret Matchett

Around the same time Käte Hey pursued and earned her PhD at the University of Hamburg, a young woman by the name of Mina Rees had a similar goal, only at Columbia University in the United States. Rees had grown up in New York City and had attended Hunter High School and then Hunter College in New York City, both institutions for women. As she explained it, “by definition, a college has a mathematics department, so at a college for women, you have to have women in mathematics! …I did what everybody did: I picked the field that I found most interesting and decided to major in it. It never occurred to me that there was anything the matter with that” [18, p. 264]. This perspective changed when Rees attempted to pursue a PhD at Columbia University. Rees had enjoyed an undergraduate course in abstract algebra and set her mind to pursuing a PhD in the field. While teaching at Hunter High School, she enrolled as a full-time graduate student at Columbia. She soon learned (unofficially) that Columbia was not interested in women pursuing doctoral degrees at that time [18].

Rees shifted her course work and earned a master’s degree from Columbia’s Teachers College in 1925; she then accepted a teaching position at Hunter College. She remained committed to finding a way to earn a PhD in mathematics, however. In 1929, when she had her finances in order, she took a leave of absence from Hunter College and left for the University of Chicago to pursue a doctorate under Leonard

[11] Not all of those associated with the Lab School remembered her so fondly. One of her former students had mixed feelings about Matchett. Since he was a much stronger student than the others in the class, Matchett encouraged him to think about how to teach the subject during class. “I became a very different sort of teacher from the typical American pure mathematician as a result” [1]. As he looked back, however, this student had “very mixed feelings about her. Like most of the Lab school faculty I was close to, she was a communist. I was very alienated from my family, so they had a great influence on me, which I have come to regret.” This particular student especially regretted attending college and graduate school early and investing a number of his early years in political activism. He later viewed his political involvement as “a stupid waste of time.” He still questions why the Lab School faculty “pushed me like that, and I am sure Ms. Matchett had a lot to do with it.”

Dickson. Rees had studied Dickson's celebrated *Algebras and Their Arithmetics* and had fallen in love with the topic. By this time, Dickson had evolved into a notably successful advisor for women pursuing PhDs in mathematics in the US in the early decades of the 20$^{\text{th}}$ century. Between 1900 and 1940, Dickson advised 8% of all women PhDs in mathematics in the US and 40% of those at Chicago [30, pp. 44–45].

Interestingly, Rees did not apply to the University of Chicago, nor did she contact Dickson about working with him. She simply appeared on his doorstep, as it were [50]. This style of arrival must have made an impression on Dickson. Traditionally, Dickson gave prospective PhD students a test problem before taking them on as students. These students had a few weeks to work on a small question so Dickson could observe their potential to take on more challenging problems. But Dickson did not give Rees this type of preliminary problem. He seems to have quickly accepted her as a student and put her to work on writing the closing chapter of his multi-year work on associative division algebras. Rees completed her PhD in 1931. Dickson's line of inquiry on associative division algebras was constructive. In contrast, with their set theoretic focus, Emmy Noether and her colleagues made Dickson's approach obsolete. So Rees' thesis work would in all likelihood not make a name for her in the research world, nor help launch a research career for her. Saunders Mac Lane suggested that perhaps Dickson did not test Rees prior to assigning her a research topic because he saw Rees as a different kind of student [38]. Since she planned to return to her position at Hunter, he may have viewed her as a talented and dedicated student with a valuable career ahead of her in teaching, but not destined for a role as a research mathematician [54]. Indeed, Rees went on to wield a profound influence on American mathematics, in particular with her keen ability to build bridges between mathematicians at universities and the government, her wartime efforts on the Applied Mathematics Panel, her influence on early uses of computers, and her broad views of education [23].[12]

In comparison, Artin did not assign Hey and Matchett a dying problem using outdated methods but, rather, a topic closely aligned with his own celebrated work and quite relevant to the contemporary mathematics of the time. Hey's work on "not a simple problem" in hypercomplex number systems took up a question at the center of the study of linear associate algebras. Matchett's work on classical zeta functions relied on the recent work of Chevalley, Artin, and Whaples and helped pave the way for John Tate's seminal results a few years later.[13]

[12]See Chap. 14 in this volume for further information about Rees and her career.

[13]In contrast, David Gilbarg, Artin's other student at IU, wrote a thesis *On the structure of the group of p-adic* 1*-units* on a topic that was not nearly as close to Artin's own area of research as that of Hey and Matchett.

3.6 Conclusion

That Artin would suggest challenging, relevant topics for his only two women PhD students indicates he had confidence in their ability to do mathematics at a high level. It seems that factors beyond mathematics—financial circumstances in the case of Hey, family responsibilities for Matchett and an environment inclined to offer positions to men rather than women—prevented their full participation in a mathematical research community. If Hey or Matchett had chosen to pursue a research career in mathematics, Artin had certainly helped put them on a path for research success.

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Chapter 4
Making Her Mark on a Century of Turmoil and Triumph: A Tribute to Polish Women in Mathematics

Emelie Agnes Kenney

Abstract New starts, new beginnings, doubt, excitement, difficulties, and positive outcomes are familiar to most mathematicians. To the women who are the focus of this paper, however, new beginnings meant relocating to a different continent or changing their focus from mathematics to mathematics education. Difficulties included learning and teaching in secret. And positive outcomes meant not only generating new results, but changing the way mathematics was taught in their country, popularizing mathematics much more extensively than ever before, and being free to investigate mathematics to whatever extent they chose. This paper introduces the particular twentieth-century experiences and accomplishments of Polish mathematicians Anna Zofia Krygowska, Zofia Szmydt, and Helena Rasiowa, among others, in the context of Poland during World War II, and acknowledges the contributions of later mathematicians whose work in a new country is ongoing and significant. To supply that context, short descriptions of the development of the Polish School of Mathematics and clandestine education in Poland are provided.

Keywords Polish women mathematicians • Clandestine education • Flying university • Polish school of mathematics • Nazi occupation of Poland

4.1 Introduction

In the twenty-year period between the world wars, Polish mathematicians formally set about constructing a framework by which the nation would become known for excellence in certain areas of mathematics. As a result of determined, coordinated efforts, faculty in Poland's powerful and renowned School of Mathematics, mainly centered in Lwów and Warsaw (Warszawa in Polish), and to a lesser extent in Kraków, specialized in and became internationally known for contributions in topology, set theory, logic and the foundations of mathematics, philosophy of mathematics, probability theory, game theory, and especially functional analysis.

E.A. Kenney (✉)
Siena College, Loudonville, NY, USA
e-mail: kenney@siena.edu

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On September 1, 1939, Nazi Germany invaded Poland, thus beginning World War II, and all formal intellectual life came to a stop. During the six-year German and Soviet occupation of Poland, formal and informal intellectual life was conducted in secret under threat of arrest, internment in a concentration camp, and death. A December 27, 1939, letter from Antoni Zygmund to Jacob Tamarkin gives a sense of the flavor of life in Poland at that time:

> I still know very little of my colleagues in other Polish towns. Of Warsaw I know nothing, except the Germans robbed the University of all laboratories, which are sent to Germany. [. . .] Some of the professors are shot [. . .] many are imprisoned. Perhaps you know from newspapers that almost the entire staff of the Cracow [sic] university was arrested and then sent to Germany.. . . Lwów is full of refugees, but the situation there [. . .] is rapidly worsening and there begins a flight of people from under the Soviet occupation to Wilno [. . .] [46].

The arrests of which Tamarkin writes are known as *Sonderaktion Krakau*, or Special Action Kraków.[1] Seven mathematicians were among the 183 people arrested at the Jagiellonian University on November 6, 1939, allegedly for starting the academic year without the Nazis' permission. Three women were immediately released, several individuals were jailed, 169 were sent to *Konzentrationslager* (KL) Sachsenhausen,[2] and some went thereafter to KL Dachau. The mathematicians were Stanislaw Gołąb, Antoni Hoborski, Adam Bielecki, Andrzej Turowicz, Stanisław Turski, Witold Wilkosz, and Tadeusz Ważewski. Hoborski died in Gołąb's arms from untreated burns following an accident with a vat of boiling soup [14], after which Adolf Hitler's men simply killed intellectuals on the spot, rather than imprisoning them first. As a direct consequence of World War II, Poland lost over 50% of her mathematicians to death from murder, starvation, and disease [15]; others emigrated.

Nevertheless, despite the almost inconceivable danger, education was carried out clandestinely throughout Poland, although it was not accessible to everyone in every village. Education has long played a significant role in Poland's history. In fact, the world's first ministry of education, *Komisja Edukacji Narodowej*, or National Education Commission, was established in Poland in 1773 [8, 39]. But at no time has the country's focus on education been more clear or more fraught with danger than in the several periods of clandestine education, the history of which actually goes back to the time of the partitions. From 1772 to 1918, Poland was divided three times among occupying forces, including Russia, Prussia, and Austria. In order to keep Polish culture alive against the wishes of the occupiers, Poles secretly embarked on a project to teach all the subjects that were forbidden, which included Polish language, history, geography, and literature. The first incarnation, from 1883 to 1905, was intended especially for women and the poor. It was during that time that the term *uniwersytet latajancy*, flying (or floating) university, came into vogue. This term represented the movement (or "flight") of education from private home to private home in order to protect secrecy [8].

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[1]The Nazis actually referred to this as *Aktion gegen Universitäts Professoren*, or action against university professors.

[2]*Konzentrationslager* is the German word for "concentration camp."

Of interest here is the second incarnation, during the war years of 1939 to 1945.[3] Despite the dangers and hardships, many professors taught and many students earned degrees in the underground, while tens of thousands of secondary students continued their education in secret. Women were involved as equals with men when it came to underground education (and fighting in a variety of ways against the occupiers): they studied, taught, and traveled around the country organizing secret classes.

After World War II, the universities resurrected themselves and secondary schools were rebuilt, although the lack of teachers because of death or inability to access appropriate pedagogical education damaged a generation. Nevertheless, despite many struggles with Soviet domination and various reform movements, Poland produced many fine mathematicians, including a significant number of women, many of whom emigrated to the United States, Canada, and other nations.

4.2 Between the World Wars: The Polish School of Mathematics

In order to understand what Poland lost in World War II—besides six million lives, three million of whom were Jewish—it is necessary to consider the successful efforts between the two world wars to build a distinctively Polish school of mathematics.

After 123 years of foreign domination ended in 1918, Poland regained its independence. To help rebuild the nation as a Polish state, the periodical *Nauka Polska: jej potrzęby, organizacja i rozwoj (Science and letters in Poland: its needs, organization and progress)* was founded. In its 1918 inaugural issue, *Nauka Polska* published two influential articles by mathematicians.[4] In the first article, Stanisław Zaręba proposed sending secondary schoolteachers abroad in order for them to learn about current research in mathematics so that they could teach in Polish universities what they had learned [53]. In the second article, Zygmunt Januszewski urged discovering mathematically talented people and having them all focus on one branch of mathematics [27]. In 1919, *Nauka Polska* published an article by Stefan Mazurkiewicz, who reviewed the 1918 articles; called for two mathematics centers in Poland; and proposed that Poland needed to recruit new talent, figure out good ways to disseminate research, and create mathematics libraries [32, 36].

Previously, Wacław Sierpiński noticed at a gathering of mathematicians at the 1911 Congress of Biologists and Physicians in Kraków that they enjoyed many discussions, but none concerning their research, since their fields did not overlap: Kazimierz Żorawski was a differential geometer; Zaręba worked in differential equations; Józef Puzyna was an analytic function theorist; Samuel Dickstein's interests were algebra, history, and secondary education; and Sierpiński specialized

[3]The third incarnation occurred in the late 1970s when Poland was under Soviet control.

[4]The translations of the titles of these articles and the page numbers were obtained from [11].

in set theory and number theory. Sierpiński wondered whether it was possible to encourage a group of mathematicians to become involved in one field so that they could talk to one another about their research [31, 32].

In 1919, Sierpiński, Januszewski, and Mazurkiewicz decided at the University of Warsaw that they would create a set theory research center. The next year, they established *Fundamenta Mathematicae*, the world's first specialized mathematics journal, which focused on research in set theory, topology, and function theory. Articles were to be published in all world languages, not only in Polish. Within a couple of years, contributors from the United States, Russia, and the Netherlands had articles published. The first contributors to the journal were intentionally Polish; they included Stefan Banach, Januszewski, Kazimierz Kuratowski, Mazurkiewicz, Stanisław Ruziewicz, Sierpiński, Hugo Steinhaus, and Wilkosz.

In Lwów, the principal educational institution was Jan Kazimierz University, the main focus was functional analysis, and the journal established there in 1929 was *Studia Mathematica*. The Lwów group included Banach, Steinhaus, Stefan Kaczmarz, Stanisław Ulam, and Marek Kac. Kraków may have been less celebrated than Warsaw and Lwów as a center of mathematical activity, but its mathematicians certainly made contributions to the subject. The main focus there was analysis, and the important institutions were the Jagiellonian University, founded in 1364, and the Academy of Mining and Metallurgy. The principal mathematicians were Zaręba, working in differential equations, Franciszek Leja, an analytic function theorist, and Antoni Hoborski and his student Stanisław Gołąb, differential geometers. Also in Kraków were Otton Nikodym, Alfred Rosenblatt (who later moved to Peru), Władysław Nikliborc (who later moved to Warsaw), and Jan Śleszyński.

In addition, significant work was undertaken by Antoni Zygmund and Stefan Kempisty at Stefan Batory University in Wilno; Zdzisław Krygowski, who worked both at the Lwów Polytechnic and at Poznań University, setting up a cryptography course[5] that later played a role in World War II; and Władysław Orlicz, who taught at Poznań University.

Further contributions to the development of a School of Polish Mathematics included the establishment of the Polish Mathematical Society in 1919 (started as the Mathematical Society of Kraków in 1917), whose founders included Steinhaus, Banach, and Nikodym, and whose foreign members included Élie Cartan, Solomon Lefschetz, Ivan Vinogradov, and Ernst Zermelo. In 1927, the first Polish Mathematical Congress was held in Kraków, the second in 1931 in Wilno, and the third in Warsaw in 1937. In this era, many distinguished foreign mathematicians visited Poland: Émile Borel, Cartan, Heinz Hopf, Henri Lebesgue, Lefschetz, Thoralf Skolem, Pavel Urysohn, John von Neumann, and Zermelo [28]. By the end of the 1930s, the development of mathematics in Poland was proceeding as envisioned by Sierpiński, Januszewski, and Mazurkiewicz [32].

[5]Marian Rejewski, Jerzy Różicki, and Henryk Zygalski were three alumni of Poznań University who broke the Enigma code, allowing them to decrypt German messages until 1938, when the process became too expensive. The Poles then instructed the French and the British in their techniques; the British, having more financial resources, eventually went on to gain much military intelligence from these decryption techniques.

4.3 World War II

On September 1, 1939, the Nazis invaded Poland, and everything changed in the most dreadful of ways for the entire country. All universities and secondary schools were closed and the intelligentsia was decimated. For the community of mathematicians, the effects were devastating: Poland lost about half of her mathematicians to death [15], while others were lost to sickness or to emigration. Despite the valiant efforts of clandestine educators, she lost an entire generation of future mathematicians and mathematics educators, either to death or lack of access to education. Universities, research centers, and entire cities were lost. The grand plans of Sierpiński, Januszewski, and Mazurkiewicz were, of course, temporarily abandoned. There was too much devastation, too much death, and too much fear of death for them to continue toward implementing their great vision for Polish mathematics.

Since an international uproar was what caused the Nazis to eventually release the Kraków professors, the Nazis thought of other means to "liquidate" professors and other members of the intelligentsia. Hans Frank, the governor of the Kraków region, wrote that

> One cannot begin to describe the trouble caused us by the Professors from Cracow [sic]. If we had taken care of the matter on the spot, the situation would have taken a completely different course. I most urgently beg you, gentlemen, not to send anyone else away to concentration camps. Either conduct a complete liquidation on the spot, or allot a punishment in accordance with the law. Any other conduct constitutes a threat to the Reich, and will result in additional troubles for us [44].

Indeed, Frank implemented his suggestion by ordering the *Ausserordenliche Befriedungsaktion*, or Extraordinary Action of Pacification, known as the *AB-Aktion*, in which tens of thousands of members of the intelligentsia were arrested, imprisoned, and either transferred to concentration camps or shot in the forests. These events were followed by what is known as the Massacre of the Lwów Professors. Those murdered include the mathematicians Włodzimierz Stożek, Ruziewicz, Antoni Łomnicki, Kaspar Weigl, and Kazimierz Bartel, all executed by firing squad. Lwów mathematicians Jan Hercberg, Marian Jacob, Ludwik Sternbach, and Menachem Wojdysławski were missing and presumed dead. Both Hermann Auerbach and Józef Schreier committed suicide by poisoning [12].

Samuel Dickstein was killed in the Nazi bombing of Warsaw in 1939, and both Stanisław Saks and Juliusz Paweł Schauder were murdered by the Gestapo in 1942 and 1943, respectively. Hoborski died in KL Sachsenhausen in 1940 in the arms of Gołąb, his student; Jozef Zalcwasser died in KL Treblinka in 1943; Aleksander Rajchman died in KL Dachau in 1941. These deaths are mere examples.

Many mathematicians were imprisoned, but either did not die or did not die immediately: Banach, who was weakened by the box of feeder lice the Nazis required him to wear in hopes of developing a typhus vaccine, died of lung cancer in 1945.[6] Karol Borsuk, Edward Marczewski (born Szpilrajn), Ważewski, Wilkosz,

[6]The mathematicians Bronisłow Knaster, Władysław Orlicz, Jerzy Albrycht, and Feliks Barański were also pressed into service as louse feeders [12].

and Gołąb survived the war. Steinhaus was successfully hidden, but possessed false documents he had been given in case he was discovered [12, 16]. Kac, Samuel Eilenberg, Jerzy Spława-Neyman, Alfred Tarski, Ulam, and Zygmund, among others, had emigrated in time to escape.

4.4 Education in the Underground

In a 1940 memorandum, Nazi SS leader Heinrich Himmler summarized the Nazi attitude to Poles and their education. He dictated that Poles should be able to write their names, count to 500, and "[recognize] that to be obedient to the Germans is a divine commandment" [45]. To such edicts, the rallying cry of Poles was, "We will not become a nation of illiterates!" In October of 1939, even before Himmler's memorandum to Hitler, the *Tajna Organizacja Nauczycielska* (*TON*), the Secret Teaching Organization, had been formed.

Eventually, throughout Poland, there were more than 10,000 students in clandestine universities and between 1,000,000 and 1,500,000 secret high school students. There were even underground medical, pharmacy, law, and seminary students, as well as secret classes in the Jewish ghettos and in concentration camps. As the war wore on, about half of Poland's professoriate was involved in "conspiratorial instruction."

Classes met in small groups, typically in private apartments; medical instruction took place in hospitals, where students pretended to be learning first aid (which was acceptable to the Nazis). If soldiers entered an apartment building downstairs, students upstairs quickly made sandwiches and started dancing, pretending the occasion was a birthday party. At each meeting, the location of the next meeting would be announced. Professors used pseudonyms. Everyone took a loyalty oath. In the years of clandestine mathematics education in Kraków, nobody ever betrayed the involvement of anyone else [14].

Of particular interest here is the participation in clandestine education of mathematicians, mathematics educators, and mathematics students, even though some of them had been imprisoned in concentration camps and knew what the consequences of their actions could be. Kraków mathematicians imprisoned in KL Sachsenhausen, KL Dachau, or both included Bielecki, Gołąb, Leja, Ważewski, and Turski. Wilkosz and Hoborski were also held in concentration camps, but Hoborski died in one, and Wilkosz, in a weakened state, died a year after release. Those who survived taught clandestinely. The legacy of three of these mathematicians was even more profound: from 1945 to 1960, all recipients of a PhD in mathematics from the Jagiellonian University studied under a professor who had taught in the underground: Leja, Ważewski, or Gołąb [25].

After the Nazis closed down the University of Warsaw weeks after their invasion, a group of professors helped to organize an underground university in the city. The mathematicians involved included Karol Borsuk, Jan Łukasiewicz, Mazurkiewicz, Sierpiński, Andrzej Mostowksi, and Kuratowski. Borsuk was caught, was jailed, escaped, and successfully hid (after the war, he and Kuratowski helped to rebuild the educational systems). Kazimierz Zarankiewicz taught in the underground, but was caught and sent to a labor camp in Germany. Władysław Ślebodziński, a Krakowian who co-founded the journal *Colloquium Mathematicum* and introduced the notion of the Lie derivative, lectured in underground university classes, was caught, and was jailed in Nazi concentration camps Auschwitz, Gross-Rosen, and Nordhausen. He survived, living a very long life. Janina Wolska (known as Janina Wolska-Bochenek after her marriage) received her doctorate in mathematics in the underground university, and went on to participate in the *Armia Krajowa* (described below) and the Warsaw Uprising, and to co-found the school of integral equations at the Warsaw Institute of Technology. Witold Pogorzelski not only taught in the underground, but prepared texts for his secret courses.

When the Nazis expelled all Poles from Poznań University and replaced them with German instructors and students, many of the Polish faculty moved to Warsaw and established the University of the Western Lands under the auspices of the Department of Education of the Polish Underground State. Teaching and learning there were clandestine. Other branches opened, as well, and these stayed open until the end of the war. The branch in Warsaw, however, operated from 1940 to August 1944, closing because of the commencement of the Warsaw Uprising, a heroic two-month battle of Poles against the Nazis. Most of the fighters in the Warsaw Uprising were associated with *Armia Krajowa*, which was the military arm of the Polish Underground State, and was the name by which the Polish resistance movement was known (although calling the movement the *conspiracy* was preferred to calling it the *resistance*). The Warsaw Uprising claimed the lives of half the faculty and untold numbers of students and other citizens (up to 200,000 civilians alone), and infuriated the Nazis to the extent that they carried out their pre-war plan to flatten the city of Warsaw.[7] After the war, Poland reclaimed the city of Poznań, and the university there was returned to Polish hands.

4.5 Education in Poland in the Immediate Post-War Period

After the war, entire cities and universities changed names, locations, or national identities. Lwów University moved to Wrocław, Poland, previously known as Breslau, Germany. Lwów itself became Lviv, Ukraine, and the University of Lwów was replaced by the Ivan Franko National University of Lviv. Wilno, Poland, became Vilnius, Lithuania, and its Stefan Batory University moved to Toruń, Poland, where it was renamed Nicolaus Copernicus University. Poland's ancient university in Wilno, established in 1579, became Vilnius University in Lithuania [44].

[7]The Warsaw Uprising was preceded by the Warsaw Ghetto Uprising in 1943, which was a one-month act of fierce resistance to the imminent complete destruction of the Warsaw Ghetto and its inhabitants. The Jews who fought there had a very small cache of weaponry, mostly provided from the meager supply of the *Armia Krajowa* and the communist *Gwardia Ludowa*. Thirteen thousand Jews perished in the Warsaw Ghetto Uprising.

The remaining universities did not stay closed for long, however; for example, 4000 students attended classes at the University of Warsaw when it reopened in December, 1945 [19], although classes had to be conducted in the rubble of the buildings [7]. The Jagiellonian University reopened in 1945, with 5000 students attending classes [26]. Poznań University (renamed Adam Mickiewicz University in 1955) reopened in February, 1945, despite continued fighting even as the war was ending [1]. The Catholic University of Lublin (now John Paul II Catholic University) had no mathematics department, but planned for one before the war. The Nazis closed the university, except to use some buildings as a military hospital, and either executed faculty and students, or sent them to labor camps in Germany or to extermination camps. The university reopened on August 21, 1944.

Besides the large public universities and technical schools that reopened, the postwar era saw the founding of many new institutions. The University of Łódż was established on May 24, 1945; the Pedagogical University of Kraków in 1946; and the Silesian University of Technology was founded on May 24, 1945, by a group of Polish professors who had formerly been employed by the Lwów Polytechnic.

Restarting the secondary schools was a more formidable task, since thousands of teachers were killed and most buildings were destroyed (except in Kraków, where the Nazis had used the buildings). Various strategies were employed to address these problems, including the establishment of pedagogical colleges and the building of new secondary schools, but the damage to the education system had consequences that took a generation to repair.

4.6 Women Mathematicians, Educators, and Students

4.6.1 The World War II Years and Mathematics: Notable Polish Women

Although both men and women participated in clandestine education, women's particular roles as teachers and students should be emphasized because, for one thing, it was in this context that some of the noteworthy Polish women mathematicians learned their science and their craft. Many women in Poland participated in the activities of *TON*, some as students and some as instructors. We focus here on seven among the many women who studied mathematics clandestinely at the university level in order to limn the varieties of experience they had and the directions their lives took, despite—and in many instances, because of—their existence in Poland during World War II. Many of these women also participated as fighters, secret teachers, or students in Poland's vast and complex underground and resistance network. Some were imprisoned and suffered as a result of the so-called medical experiments; others were among those murdered outright by the Nazis. After the war, some women maintained careers in mathematics research, some focused on teaching and popularization, others specialized in related areas, such as logic and philosophy, and others gave up the field entirely in favor of careers in astronomy or medicine. All of them have stories well worth our telling and remembering.

4.6.1.1 Maria Kusmierczuk (1920–1989)

Kusmierczuk was born in Zamość, Poland. On September 1, 1939, the first day of the Nazi invasion, Kusmierczuk was a second-year student at Stefan Batory University, established in Wilno in 1579. She focused on mathematics and other scientific subjects. As was typical for patriotic Poles of the day, she joined the underground to fight for her country in any way she could. On November 9, however, she was arrested and brought to the jail in Lublin, after which she was interred in KL Ravensbrück, where she was tortured by injections of bacteria into her legs, which caused terrible mutilation.[8] With a group of women, Kusmierczuk walked back to Poland when KL Ravensbrück was closed in April 1945. After the war, Kusmierczuk was lost to the field of mathematics, but not to science: in 1952, she earned a medical degree from the medical college in Gdańsk. She worked as a radiologist in Gdańsk with cancer patients.

4.6.1.2 Helena Rasiowa (1917–1994)

Rasiowa entered the University of Warsaw in 1938, but, after the 1939 Nazi invasion and subsequent occupation, formal university study was difficult and eventually impossible since the Nazis shut down Poland's universities within months of their occupation. Rasiowa managed to study in the underground university, clandestinely earning a master's degree under the supervision of the noted logicians Bolesław Sobociński and Jan Łukasiewicz. In 1944, though, in retribution for the sixty days of the heroic Warsaw Uprising, the Nazis demolished the city of Warsaw. Rasiowa and her mother escaped the destruction, but their house and her thesis did not.

Rasiowa taught in a secondary school after the war. The mathematical logician Andrzej Mostowski encouraged her to return to her own studies, which she did, rewriting her master's thesis in 1945. Five years later, she was awarded the PhD from the University of Warsaw, writing her dissertation *Algebraic Treatment of the Functional Calculi of Lewis and Heyting* under Mostowski's supervision. In 1956, she earned her DSc from the Institute of Mathematics of the Polish Academy of Science [6].

In her long, influential career, Rasiowa wrote three books and approximately 98 articles. Her research involved algebraic logic, the foundations of theoretical computer science, and the relations between these fields. Mainly because of her efforts, the international journal *Fundamenta Informaticae*, focusing on the mathematical foundations of computer science, was established in 1977. In addition, Rasiowa engaged in editorial work for *Studia Logica* and the *International Journal of Approximate Reasoning*. In the year of her death, Rasiowa remained hard at work; one of her last publications, appearing in 1994, was *Axiomatization and Completeness of Uncountably Valued Approximation Logic* [43]. In 2001, the

[8]The United States Holocaust Memorial Museum holds in its collections a clandestinely obtained photograph of Kusmierczuk's disfigured leg. See Photograph #69339 at collections.ushmm.org.

Warsaw University Press published *Algebraic Models of Logic*, based upon the unpublished manuscripts on which she was working at the time of her death; her working title was *Algebraic Analysis of Non-Classical First Order Logics* [6].

Rasiowa's service to the profession included involvement with the Polish Mathematical Society, the Association for Symbolic Logic, and the International Union of History and Philosophy of Sciences.

4.6.1.3 Zofia Szmydt (1923–2010)

Szmydt earned a master's degree in 1946 from the Jagiellonian University, founded in 1364 and also known as the University of Kraków. One imagines she did at least some of the work clandestinely during the war, given the year she earned her degree. She received her PhD in 1949, also from Jagiellonian University, under Ważewski, one of the seven mathematicians imprisoned in KL Sachsenhausen after *Sonderaktion Krakau*. Szmydt's dissertation was on partial differential equations.

Szmydt's interest in differential equations continued after she graduated, eventuating in the publication of the important works *Fourier Transformations and Linear Differential Equations*, *Topical Embedding of Laplace Distributions in Laplace Hyperfunctions*, and *The Mellin Transformation and Fuchsian Type Partial Differential Equations*, the latter two with Bogdan Ziemian, one of her PhD students at the Polish Academy of Sciences. Szmydt was known as a sophisticated instructor who gave smooth presentations; as a person, she was thought of as very generous, but somewhat averse to attending social functions. Roman Sznajder, who took six courses with her, recalls attending the International Congress of Mathematicians in 1978 in Helsinki with Szmydt. She gave Sznajder her invitation to attend a reception at the home of the Mayor of Helsinki, since he did not have one. She also kept on hand a supply of restaurant coupons so that her students could eat for free [48–50].

In 1956, Szmydt became the first woman to win the Stefan Banach Prize of the Mathematical Institute of the Polish Academy of Sciences for her work, done in a series of six papers, in applying Ważewski's topological method to the study of nonlinear ordinary differential equations [34].[9]

4.6.1.4 Janina Hosiasson-Lindenbaum (1899–1942)

Janina Hosiasson was known as a talented logician; her life was tragically ended by a Nazi bullet. She studied philosophy and logic, particularly inductive logic, at the University of Warsaw, where she attended lectures by Kazimierz Ajdukiewicz, Tadeusz Kotarbiński, and Jan Łukasiewicz. In 1926, she earned her doctorate under

[9]Other mathematicians from the era who won this prize include: Steinhaus and Sierpiński, Władysław Orlicz, Stanisław Mazur, and Adam Bielecki. Bielecki was one of the victims of *Sonderaktion Krakau*; after the war, he went on to have eleven PhD students.

Kotarbiński, and, in 1929, she moved to Cambridge with funding from the Polish Ministry of Religious Affairs and Public Education [54].

Writing over 20 articles (as well as translations of some of Bertrand Russell's works), Hosiasson focused her research primarily on induction and the application of probability theory to inductive logic. Though she published other articles, she was noted especially for her exegesis of the Raven Paradox (called Hempel's Paradox because of his 1945 article in *Mind* [17, 18]). Her article *On Confirmation* was published in the *Journal of Symbolic Logic* in 1940, five years before the publication of Hempel's article [22]. Saunders Mac Lane reviewed her article in the *Journal of Symbolic Logic* [35].[10]

In September 1941, she and her husband, the mathematician Adolf Lindenbaum, were arrested by the Nazis in different cities (they were living separately at the time), he in Białystok, she in Wilno. She was imprisoned in Wilno until April 1942, when the Nazis moved her to a nearby village, where they shot her.[11]

4.6.1.5 Irena Gołąb (1903–2008)

Irena Sokulska studied at Kraków's Jagiellonian University, taking her degree in philosophy, as were called all degrees in natural science and mathematics at the time, since these departments were housed within the Faculty of Philosophy; she then sat for her teacher's examination at the university in Poznań. Since mathematics teachers were in demand at the time, she decided to become a teacher of mathematics in a *gimnazjum*, or gymnasium, which, in the Polish system, is a compulsory middle school for students aged 13 to 16. While studying in Kraków, she met Stanisław Gołąb, who taught and conducted research at the Jagiellonian University. They met again later in Rome and eventually married.

Stanisław Gołąb was one of the seven mathematicians arrested at the university, jailed, and taken to KL Sachsenhausen in the infamous Nazi action *Sonderaktion Krakau*. Later, he was sent to KL Dachau, from where he was eventually released, although in poor physical condition.[12] He taught in the underground classes at the Jagiellonian University, which started in 1942, and after the war he guided at least 20 PhD students. Over the six-year occupation of Poland, Irena Gołąb ran clandestine mathematics classes in their home. Always at hand were materials for crocheting in case the Nazis made an unexpected visit. Her crochet circles of students served to protect the students from the Nazis, who forbade learning any mathematics beyond simple counting, as noted above. Had she not taken these preventative steps, and had she and her students been caught, they all would have been arrested. After the war, she taught mathematics in a technical high school [14].

[10] For a detailed discussion of logic in this era, see [52].

[11] It is not clear when and where Adolf Lindenbaum was murdered, only that he was [54].

[12] At 167.64 cm (5' 6"), he weighed only 42 kg (92.5 lb) upon his return to Kraków.

4.6.1.6 Wanda Szmielew (1918–1976)

Szmielew began her university studies at the University of Warsaw in 1935. There, she met logicians Alfred Tarski and Adolf Lindenbaum, and, in 1938, produced her first result, on the Axiom of Choice for finite sets. World War II interrupted her formal studies, however, so Szmielew worked as a surveyor while simultaneously studying and teaching in the underground. In fact, she began her work on the topic of her dissertation during the war. Her first paper was not published until 1947, the same year she earned a master's degree from the University of Warsaw [47].

Szmielew taught at both the University of Łódź and the Łódź Institute of Technology. She was a pioneer at the University of Łódź, which was founded in 1945. She spent 1949 to 1950 at the University of California, Berkeley, where she earned her PhD under the guidance of Tarski, who had left Poland in 1939. Her dissertation, *Arithmetical Properties of Abelian Groups*, contained a proof of the decidability of abelian groups. From 1950 on, she held a position at the University of Warsaw.

Szmielew published at least 26 articles, several with Karol Borsuk and some with Tarski. In what seems typical of the work of Polish women mathematicians, she was interested in relationships between different branches of the field. Her 1981 book was published in 1983 in English as *From Affine Geometry to Euclidean Geometry: An Axiomatic Approach*. In it, she examined connections between geometric systems and corresponding algebraic theories, according to Maria Moszynska, who finished the book with minor changes as Szmielew's health failed [29]. In general, we can say that Szmielew's research focused on foundations of algebra, foundations of geometry, set theory, and relationships among the three fields.

4.6.1.7 Zofia Krygowska (1904–1988)

She was born Anna Zofia Czarkowska, but was known professionally as Zofia Krygowska and, after her marriage, as Anna Zofia Krygowska. Her original intention did not include becoming a monumentally influential figure in the theoretical underpinnings of mathematics education, although that was what she became. Her early education took place in the mountain town of Zakopane, after which she entered the Jagiellonian University, where she was a student from 1923 to 1927 in the Faculty of Philosophy, earning her master's degree in 1931.

During World War II, Krygowska's official work was as an accountant in a lumber company [10]. At the same time, she traveled around Poland under the auspices of *TON*, in order not only to teach mathematics classes, but also to help organize and coordinate these secret classes. All of this was done under pain of death by Nazis if caught.

When the war ended in 1945, there was a shortage of schoolteachers, since many teachers were killed during the war and many aspiring teachers were unable to access clandestinely the education necessary to qualify as a teacher. Krygowska spent many years as an elementary and high school teacher, a profession she began as a student prior to completing her PhD. Her 1950 doctoral thesis, *On the Limits of Strictness (Rigor) in the Teaching of the Elements of Geometry*, was produced under the direction of Tadeusz Ważewski at Jagiellonian University. In her thesis, she developed a new set of axioms for geometry and showed that they are equivalent to Hilbert's system.

Witold Wilkosz, one of the mathematicians arrested in *Sonderaktion Krakau*, as was Ważewski, inspired Krygowska. Otton Nikodym was also a source of inspiration for her. All of them were interested in mathematics and in mathematics education. They aimed to present to students the new ideas in professional mathematics—set theory, mathematical logic, and topology—as precisely and as rigorously as possible, but maintained that these presentations must be absolutely clear to the student, or they were worse than useless. Krygowska particularly wanted to know the best ways of bringing the so-called school mathematics closer to professional mathematics.

Eventually, Krygowska, among many workers in mathematics education, contributed to the development of a new field of scientific questioning, called *didactics of mathematics*, which brought together mathematics, education, psychology, and the methodology of science to answer questions about how students learn, why they make the mistakes they do, how each student can be taught, and so forth. According to the then-prevailing view, mathematics can be understood by only a few bright students who will learn no matter how they are taught. Krygowska disagreed.

As Professor at the Pedagogical University (originally Pedagogical College) in Kraków from 1949 to 1974, Krygowska led the Department of Didactics of Mathematics. But her contributions to the profession did not end with her role as a university researcher and instructor. She became noted as a popularizer of mathematics and supporter of school mathematics teachers; Polish State Television broadcast a series of lectures for teachers, called *TV–University for Teachers*, which Krygowska was involved in creating, from 1968 to 1977 [9]. She was a participant and leading figure in mathematics and mathematics education conferences and societies; for example, she organized meetings in Poland of the International Commission for the Study and Improvement of the Teaching of Mathematics in 1960 and 1971. She was a member of the Polish Subcommittee of the International Committee on Mathematical Instruction of the International Mathematics Union (IMU), served as an editorial board member of didactics journals as well as mathematics journals, and lectured in France, Italy, Russia, Germany, and Canada. In short, Krygowska's far-reaching influence on mathematics education and the profession was substantial [37].[13]

4.6.2 The World War II Years and Mathematics: Additional Polish Women of Note

We mention here several other Polish women who studied mathematics from this time period, even though some of them became philosophers, logicians, or

[13]For further reading on modern mathematical didactics, see, for example, [42].

astronomers. At the time, there were strong connections among mathematicians, logicians, and philosophers, so they bear inclusion.

4.6.2.1 Janina Kotarbińska (1901–1996)

Kotarbińska was born Dina Sztajnbarg, but for self-preservation during the occupation she hid her Jewish ancestry by using the pseudonym Janina Kaminska. After she married Tadeusz Kotarbiński, her mentor at the University of Warsaw, she was known as Janina Kotarbińska. During the war, Kotarbińska participated in clandestine education, was caught, and was imprisoned in KL Auschwitz as a result. Surprisingly, the Nazis never discovered she was Jewish. She eventually became Professor of Logic and Methodology of Science at the University of Warsaw and, later, the Chair of the Department of Logic at the same institution [30].[14]

4.6.2.2 Izydora Dąbska (1904–1983)

In 1927, Dąbska received her PhD from Jan Kazimierz University, Lwów, under Kazimierz Twardowski, although she was a follower of Kazimierz Ajdukiewicz as well. Dąbska was a logician and philosopher of science; her research comprises 300 works, including 11 books. When Twardowski retired, she left Jan Kazimierz University and embarked on an eight-month tour of Vienna, Berlin, and Paris, thanks to the National Cultural Fund. Upon her return to Lwów in 1930, she taught in a secondary school. During World War II, she worked as a nurse, a member of *TON*, and a freedom fighter with *Armia Krajowa*.[15] After the war, she moved to Gdańsk, where she worked as a librarian and then as a lecturer at the University of Gdańsk. In 1957, she became a member of the faculty at the Jagiellonian University, earning the position of full professor before her retirement. Unfortunately, she was censored by the Communist Party and lost permission to publish popular articles [30].

In 1969, Dąbska became the first woman appointed to the *Institut International de Philosophie* in Paris [41].

4.6.2.3 Seweryna Luszczewska-Romahnowa (1904–1978)

In 1932, Luszczewska-Romahnowa earned her PhD under Twardowski in Lwów. She also studied philosophy there with Kazimierz Ajdukiewicz and Roman Ingarden, as well as mathematics with Banach and Steinhaus. During World War II, Luszczewska-Romahnowa became a prisoner in Nazi camps, including KL

[14] See [52] for background details.

[15] The Jewish units of the *Armia Krajowa* were the Jewish Military Union and the Jewish Combat Organization.

Majdanek, KL Buchenwald, and KL Ravensbrück. After almost two years of imprisonment, she escaped a column of POWs. After the war, she taught at the Adam Mickiewicz University in Poznań, where she had at least three doctoral students [30].

4.6.2.4 Wilhelmina Iwanowska (1905–1999)

Initially a student of mathematics, Iwanowska earned her MSc in analytic functions under Juliusz Rudnicki at Stefan Batory University in Wilno. She loved astronomy even more than mathematics, however, and earned her PhD in that field in 1933 and her *habilitation* degree four years later.[16] It is well known that Stefan Batory University was an underground teaching site; given this fact, there is a strong possibility that Iwanowska participated as a teacher during the war. The planetoid 198820 was named *Iwanowska* in her honor [48–50].

4.6.2.5 Rozalia Szafraniec (1910–2001)

In 1934, Szafraniec earned her master's degree in mathematics at the University of Warsaw under Sierpinski. During the war, she was not only a teacher of mathematics, but also a soldier in *Armia Krajowa*, the Home Army, fighting against the Nazis. Seven weeks before their wedding, the Nazis killed her fiancé by burning him to death. She taught mathematics after the war while working in the observatory at the Jagiellonian University. In 1950, Szafraniec earned a PhD in astronomy and worked as a professor of astronomy for the rest of her academic career [48–50].

4.6.2.6 Edith Hirsch Luchins (1921–2002)

Even though Luchins left Poland for New York City in childhood, we include her here because of her interests and accomplishments. Luchins started out her academic life deeply interested in mathematics, earning her first degree in 1942 from Brooklyn College. Various jobs, marriage, and the births of five children were interspersed with research and her own education. She earned her PhD from the University of Oregon in 1957, writing *On Some Properties of Certain Banach Algebras*. The first woman ever appointed Professor of Mathematics at Rensselaer Polytechnic Institute, Luchins had a keen interest in educational psychology as well as the history of women in mathematics [38].

[16] A habilitation is a second doctorate, the demands of which vary from country to country and over time. In general, one pursues significant independent research without the guidance of an advisor in order to be habilitated. At one time in Poland's history, submission of a successful habilitation thesis resulted in a Doctor of Science degree, denoted by DSc. At present, the designation is *doktor habilitowany*, denoted by *dr. hab.* before the recipient's name.

4.6.3 Mathematics in Poland After the War

During the years that followed the end of World War II, new regimes took over Poland, bringing the nation and its citizens new challenges and difficulties. Poland, specifically, "the People's Republic of Poland," was a satellite of the Soviet Union from 1945 to 1989, so the cherished independence experienced in the interwar years was once again lost. Immediately after World War II, members of the *Armia Krajowa* were rounded up and executed. Other Polish citizens were deported to the USSR. Eventually, reforms were instituted, and these reforms—universal health care, new hospitals, free universities, modern sports facilities—gave to Poles a sense of relief after the staggering losses of World War II. Nevertheless, repression slowly became the order of the day. Protests and demonstrations in 1968 and 1980 by laborers, students, and ordinary citizens against price rises and repressive measures were put down, often brutally. The Catholic Church was particularly subjected to persecution, which alienated most Poles, who, at this stage of Poland's history, were almost uniformly Catholic (and uniformly ethnically Polish). Given the murder of the Jews and other minorities and the redrawing of Poland's borders, Poland now was a strikingly homogeneous nation. In a way, the Catholic Church was strengthened because of these developments. As a result of that strengthening, of Kraków's Cardinal Karol Wojtyła's ascension to the papacy as Pope John Paul II, and of the emergence of *Solidarność* (Solidarity) and the rise of the independent labor union movement, Poland was ready and empowered to shed her affiliation with Communism and the Soviet Union in 1989.

The advent of capitalism and a free-market economy, however, was not without its own troublesome consequences. Whereas homelessness was not a problem before the fall of communism, it was now clearly visible, with the elderly sleeping on concrete in the cities. Health care workers and teachers did not earn the same decent salary that they would have earned in communist times. The entire economy was privatized, which meant that citizens who believed they had a share in Poland, as they had in the communist era, had nothing; only wealthy Poles and foreign investors owned the means of production, the land, businesses, and other enterprises. High unemployment, hunger, and costly apartments became the norm.

In the world of mathematics, change was at hand at each stage, as well. New generations of women and men entered the field of mathematics after the war ended, some making contributions as researchers, some as educators, or both. Quite a number of World War II survivors left the country for the United States, Canada, or other nations in hopes of finding employment at the university level. Even before the war, there were not many university positions in Poland and many mathematicians took employment at secondary schools. After the war, the university employment situation was initially worse because of infrastructure problems, which included destroyed buildings, burned libraries and stolen books, and so forth. Nevertheless, Poland rebuilt her academic institutions and opened new ones.[17] Sierpiński, Kuratowski, Borsuk, Mazur, Mostowski, and others set about reconstructing a mathematical life that, while it did not closely resemble pre-war plans for the field in Poland, laid the foundation for a respectable, productive research scene. Life slowly (or so it may have seemed to those who lived through it) improved, yet because of her highly organized underground, Poland was actually quicker to pick up the pieces of a broken academic life than many other nations that suffered through World War II.

4.6.4 Contemporary Polish Women in Mathematics

We mention here some of the contemporary women of Polish heritage who moved to the West as early as 1969, together with comments about their backgrounds, contributions, and honors. Most of these women earned at least their master's degrees from Polish universities, and all but two of them earned their doctorates there. All of them are talented and respected mathematicians.

4.6.4.1 Nicole Tomczak-Jaegermann

Tomczak-Jaegermann earned her PhD in 1974 at the University of Warsaw under Aleksander Pelczynski. Her research centers on asymptotic geometric analysis, infinite dimensional Banach space theory, and the relationships between them. She moved to Canada in 1983. A Professor of Mathematics at the University of Alberta and holder of the Research Chair in Geometric Analysis, Tomczak-Jaegermann is the winner of the 2006 CRM-Fields-PIMS Prize for exceptional research in the mathematical sciences.[18]

4.6.4.2 Krystyna Kuperberg

Currently the Alumni Professor in the Department of Mathematics at Auburn University, Kuperberg earned a master's degree from the University of Warsaw in the late 1960s, studying topology with Karol Borsuk. She left Poland in 1969, moving first to Sweden. Under W.H. Jaco, she was awarded the PhD from Rice University in 1974. She focuses her research on topics in topology, discrete geometry, and

[17]To name but a few: Marie Curie-Skłodowska University in Lublin, 1944; University of Łódź in 1945; University of Szczecin in 1945; Nicolaus Copernicus University in Toruń in 1945; the Pedagogical University of Kraków in 1946; Wrocław University of Environmental and Life Sciences in 1951.

[18]This award is given jointly by the Centre de Recherches Mathématiques, the Fields Institute, and the Pacific Institute for the Mathematical Sciences.

topological aspects of dynamical systems. Kuperberg solved Knaster's problem on bi-homogeneity of continua, and constructed a smooth counterexample to the Seifert Conjecture. Her honors include the Alfred Jurzykowski Award of the Kosciuszko Foundation. In 1998, she was an Invited Speaker at the International Congress of Mathematicians (ICM) in Berlin, and in 1999, she was the Association for Women in Mathematics (AWM) Noether lecturer [5]. As of 2012, Kuperberg is a fellow of the American Mathematical Society (AMS) [2].

4.6.4.3 Irena Lasiecki

Lasiecki earned her PhD from the University of Warsaw in 1975 under Andrzej Wierzbicki and is currently Commonwealth Professor Emerita at the University of Virginia and University Distinguished Professor at the University of Memphis. Her research concerns optimization and control theory, nonlinear partial differential equations, dynamical systems, and numerical analysis. Author of over 300 research papers and several books, she has supervised more than 20 doctoral students and at least 10 post-doctoral fellows. Her awards include the 2011 Society for Industrial and Applied Mathematics (SIAM) W. T. and Idalia Reid Prize for contributions to differential equations and control theory [51].

4.6.4.4 Bozenna Pasik-Duncan

Pasik-Duncan earned a master's degree in mathematics from the University of Warsaw in 1970 and earned two doctorates in mathematics, a PhD in 1978 and a DSc in 1986, from the Warsaw School of Economics. A researcher in stochastic systems and stochastic adaptive control, system identification and estimation, and control education, and author of over 150 articles and three books, Pasik-Duncan has nonetheless found time for active involvement with a number of professional organizations, including the Institute of Electrical and Electronics Engineers (IEEE) Control Systems Society (CSS), the International Federation of Automatic Control (IFAC), and SIAM.

Her awards and honors include the AWM Louise Hay Award for Contributions to Mathematics Education in 2004 and the IEEE Third Millennium Medal [3]. She has been named an IFAC Fellow, an IEEE Fellow, and a Distinguished Member of the IEEE CSS [23]. In 2004, she was the AWM Etta Z. Falconer Lecturer [4].

Currently, Pasik-Duncan is Professor of Mathematics at the University of Kansas, where she is also Information and Telecommunication Technology Center Investigator and Courtesy Professor of Electrical Engineering and Computer Science and of Aerospace Engineering.

4.6.4.5 Izabella Laba

Laba received her MSc from Wrocław University under Piotr Biler, and, in 1994, her PhD from the University of Toronto under Israel Michael Sigal. Her research areas include harmonic analysis, geometric measure theory, additive combinatorics, and combinatorial number theory; she has also done research in mathematical physics and partial differential equations.

Laba has served on committees of the Canadian Mathematical Society, AWM, AMS, and the Mathematical Association of America. In addition, she serves or has served on the editorial boards of the following journals: *Analysis and PDE*, *Canadian Journal of Mathematics*, *Canadian Mathematical Bulletin*, *SIAM Journal on Discrete Mathematics*, and the *Online Journal of Analytic Combinatorics*.

Her honors and awards include being named a Fields Institute Fellow in 2009, an AMS Fellow in 2012 [2, 21], and an AWM Etta Z. Falconer Lecturer in 2016.

She is at present Professor in the Department of Mathematics at the University of British Columbia.

4.6.4.6 Agata Smoktunowicz

Smoktunowicz received her PhD from the Institute of Mathematics of the Polish Academy of Sciences in 2000. Her research focuses on general ring theory and non-commutative algebra. She has shown that simple non-commutative nil rings exist and that the Artin-Stafford Gap Conjecture is true. Smoktunowicz held the J. W. Gibbs Instructorship at Yale University from 2003 to 2005 and the Emmy Noether Professorship at the University of Gottingen in 2011.

Smoktunowicz was an invited speaker at the 2006 ICM in Madrid. She has won many prizes in Europe, including the Wacław Sierpiński Prize, the Whitehead Prize of the London Mathematical Society, and the European Mathematical Society Prize [20, 33]. She is a Professor in the School of Mathematics at the University of Edinburgh.

4.6.5 Women in Mathematics in Poland Today

Currently, Poland's universities boast faculties that include significant numbers of women. A review of rosters from 2016, readily available on university websites, indicates that, for example, of the approximately 344 people associated with the Faculty of Mathematics, Computer Science and Mechanics of the University of Warsaw (MIMUW), there are 34 women holding at least one doctorate and 25 women holding a master's degree [13]. At Poznań's Adam Mickiewicz University, 27 of 132 members of the Faculty of Mathematics and Computer Science holding at least one doctorate are women [1]. Of the 78 people with at least one doctorate at the

Institute of Mathematics of the Jagiellonian University in Kraków, 15 are women, and at least 14 of 44 doctoral students are women [24].

In 2016, several members of the European Mathematical Society formed Polish Women in Mathematics (PWM), an organization dedicated to promoting women working in mathematics in Poland [40]. The aims of the association include ensuring that women in Poland find support and encouragement throughout their careers, facilitating contacts between Polish women mathematicians, and forging bonds of cooperation between PWM and its sister organizations, such as AWM, throughout the world. As of 2016, officers include, among others, Stanisława Kanas and Barbara Pekala of the University of Rzeszow, Urszula Forys of MIMUW, and Katarzyna Szymańska-Dębowska and Zofia Walczak of the University of Łódż. The future of Polish women mathematicians appears to be in good hands indeed.

4.7 Questions for Further Investigation

There are many open questions about women's participation in mathematics and in mathematics education in Poland during and immediately after World War II. The women profiled above in Section 4.6 represent a small subset of the many women who studied and taught mathematics clandestinely during the war and who started or continued their studies or their teaching afterward; we know even less about the women who suspended or permanently stopped their studies during this time. This initial list of open research questions suggests just how much we do not know.

In 1946, a year after the end of World War II, 16 students, 11 of them women, earned master's degrees in mathematics from the Jagiellonian University in Kraków. These women included Pelagia Brzoza, Alina Dawidowicz, Marta Galuszka, Zofia Oberska, Irena Palka, Barbara Peryga, Maria Saradynska, Elzbieta Setlak, Stanisława Stachnik, Zofia Szmydt (whom we discussed above), and Olga Tyrcha. It should be clear from the year each earned her degree that many, if not most of them, must have begun or continued their studies in the underground. What did they do after 1946? Did they pursue careers in mathematics?

In the seven years after World War II, 18 scholars, including five women, earned doctorates in mathematics from the Jagiellonian University. The women were: Zofia Szmydt, Zofia Krygowska, Zofia Mikolajska, Halina Pidekowna, and Krystyna Tryuk. We know that Szmydt and Krygowska studied and worked in the underground. What of the others? And what did they do after earning their PhDs?

The fate of Polish universities as a result of World War II was not uniform. How did the women in Warsaw fare compared to the women in other university centers? For example: Warsaw was reduced to a smoldering pile of rubble during the war; Kraków was not. The University of Warsaw was closed on September 27, 1939. It ceased to exist as a formal entity during the war; the contents of its Warsaw buildings were stolen and the buildings themselves were destroyed. In contrast, the Jagiellonian University, located in Kraków, was still standing after the war because the Nazis used the city as the base of what they called the *Generalgouvernement*.

What about the women who studied at the University of Warsaw or the University of the Western Lands, both in Warsaw, or Jan Kazimierz University in Lwów, or Stefan Batory University in Wilno? As noted earlier, the universities in those cities are not the same; they no longer even have the same names. Who were the women who once walked the halls, studied in the libraries, conferred with their professors or colleagues, and what became of them during and after the war? How were the paths of women mathematicians and students of mathematics affected by such differences in their circumstances?

Although answers to these questions may not come easily or even be possible to find, seeking them will be a worthwhile venture. The stories of all these women bear repeating and researching, for theirs are the stories of women who persevered in the face of adversity during a most remarkable and difficult time in the modern history of Poland.

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Chapter 5
Toward a Documentary History of American Women Mathematics PhDs: The Doctoral Classes of 1940–1959

Margaret A.M. Murray

Abstract In 1993, I started to compile a database of biographical information on the roughly 200 women who earned PhDs in mathematics from US colleges and universities during the 1940s and 1950s. At the time, my primary motivation was to locate and interview as many of those still living as I reasonably could. My book, *Women Becoming Mathematicians* (MIT Press 2000)—while providing an overview of the entire group—was devoted in the main to what I had learned by conducting oral history interviews with 36 of the women. In recent years, I have returned to the task of completing the database and publishing it online. In this essay, I describe the personal motivations that led me to this project, surprises that emerged in the course of my research, and my ongoing efforts to complete and publish the database. In light of the trailblazing work of Green and LaDuke on the pre-1940 doctorates, and the project of Leggett and Case on PhDs of the 1960s and 1970s, I see this work as key to a larger program of compiling a documentary history of the first century of American women mathematics PhDs.

Keywords Women mathematicians • Women's history • Graduate study • 20th century • US women

5.1 A Personal Introduction

At the start of my professional career, I was a research mathematician: I completed a PhD in harmonic analysis at Yale in 1983 and started a tenure-track job at Virginia Tech that same year. Then in my mid-twenties, I was young, ambitious, goal-directed, and scared. I enjoyed teaching, yes—but when it came to research, publication, and tenure, I was intrigued, obsessed, and terrified. I worked on grants and mathematical collaborations and even a book project; I traveled extensively and held visiting faculty positions—back when visiting faculty were actually *visiting*

M.A.M. Murray (✉)
Department of Rhetoric, University of Iowa, Iowa City, IA, USA
e-mail: margaret-a-murray@uiowa.edu

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from somewhere else. When I finally earned tenure in 1990, I felt exhausted by the effort and in need of respite. I bought a house, settled down, and gave myself permission to pause and reflect on both life and work.

When I got tenure, I was just past 30. For a decade or more, I had held a wide range of nonmathematical interests at bay: the arts, history, and, above all, writing. I hoped that, post-tenure and with the gift of "academic freedom," I would be able to broaden my scholarly horizons to encompass these other fields. I was also still single, in a college town where social life was built around couples and families. Among the female professors I knew, nearly all were married; among the few female mathematicians I knew, most were married to male mathematicians. To complicate matters further, I had only recently come out as lesbian. And I'd long known, even when I was dating men, that I didn't want to date a fellow mathematician: I wanted my life to be about more than just math.

In short, I felt lonely and isolated and singular. Of course, I sought out kindred spirits, as colleagues and friends and potential partners. But, for perhaps the first time in my adult life, I consciously sought role models, too. I sought them among the living—and also among the dead, in the pages of women's history and biography. There, I went looking for independent, professional women like me, wondering how they'd made their way in the world in more challenging times than mine.

The more I read, the more I felt drawn to the idea of writing the biography of an early 20th-century woman mathematician. It seemed the sort of scholarly project that my departmental colleagues might accept, if grudgingly, as "research." While looking for an appropriate subject, I stumbled onto a paper by Judy Green and Jeanne LaDuke [6], which included a brief sketch of the life of Olive Hazlett (1890–1974), a 1915 University of Chicago PhD who never married, traveled widely, and was perhaps the most productive American woman research mathematician before the Second World War. I thought, with some excitement, "Here's my subject!" Then, seeking advice—and role modeling—among the living, I decided, in May of 1993, to contact Green and LaDuke.

Both women were research mathematicians who had become historians of mathematics. While I didn't know either one of them, I suspected I'd need their help and guidance and, perhaps, their blessing. I chose to call Jeanne LaDuke first, thinking that, perhaps because she lived in my hometown of Chicago, we might have a good rapport. In our conversation—the first of many I would have with both Jeanne and Judy—Jeanne was patient, kind, and generous. She did, however, discourage me from undertaking a Hazlett biography, for to do so would mean treading on their scholarly turf. Jeanne, apologetic for being "proprietary," informed me of the full scope of their project. Since the late 1970s, they'd been chronicling not just the life of Hazlett, but the lives and careers of all 228 American women who'd earned PhDs in mathematics prior to 1940.

But Jeanne did more—much more—than shoo me away from Hazlett; she made a magnificent suggestion: "Why don't you look at the American women who earned PhDs in the Forties and Fifties?" This was, she said, an interesting "transitional period," and since many of the women were still living, I could talk with them directly. The idea appealed to me right away: I would actually be able to *meet* and talk with my mathematical foremothers, the role models I'd been seeking! And so my own project began.

5.2 Surprises in the Data

I started my research with some basic misconceptions. I imagined, somehow, that once the first woman had done it, the numbers of women earning PhDs in mathematics would subsequently increase over the years—perhaps in a basically linear fashion. And I imagined that, as women earned an increasing share of doctorates awarded, these gains would, eventually, begin to level off. But the true story, like life, was messier and more complicated.

My alma mater, Yale, was the first American university to award a PhD in any subject, and the first to award a PhD in mathematics, during the academic year 1861–1862 [17]. American *women* did not earn PhDs in mathematics until two decades later. Winifred Edgerton (later Merrill; 1862–1951) was the first American woman actually awarded a mathematics PhD when, in 1886, she received her degree from Columbia University [6, p. 123]. But she was not, in fact, first woman to *earn* a mathematics PhD. That distinction belongs instead to Christine Ladd (later, Ladd-Franklin; 1847–1930), who completed all requirements for her PhD at Johns Hopkins in 1882. Hopkins had admitted Ladd to graduate study in mathematics four years previously, where she had the support and respect of J.J. Sylvester and her adviser, Charles Sanders Peirce. But when she applied to actually receive the degree, the Hopkins administration denied her request on the grounds that it did not grant degrees to women [5; 6, pp. 120–123]. Hopkins did not, in fact, award a doctorate to a woman until 1893 [18, p. 44], and it did not award a mathematics PhD to a woman until 1911 [7, p. 57].

As for Ladd-Franklin, she pursued an active professional life, essentially retraining herself for a career as a research psychologist. Indeed, on the strength of her contributions to the theory of color vision, the Johns Hopkins University sought, in 1926, to bestow upon her an honorary Doctor of Laws degree. In lieu of this honor, Ladd-Franklin requested that Hopkins award her the mathematics doctorate she had earned over 40 years earlier. And so Ladd-Franklin became the *eighth* woman actually awarded a Hopkins math PhD [7, p. 57].

In the 40 years separating Edgerton's achievement from Ladd-Franklin's, a surprising number of American women earned doctorates in mathematics. Table 5.1 provides data for the years prior to 1930.

These data show that, in the four decades prior to 1920—the year the 19th Amendment to the US constitution gave women the right to vote—women earned a steadily increasing share of US mathematics doctorates. And, around the same time that US women began voting, their share of the mathematics doctorates did, indeed, begin to level off. While I had anticipated some sort of leveling, I had not expected it to happen quite so early.

Table 5.1 Mathematics PhDs Awarded in the US, 1862–1929

Years	Total PhDs Awarded	PhDs to Women	Women as Percent of Total
1862–1869	3	0	0.0
1870–1879	10	0	0.0
1880–1889	32	1	3.1
1890–1899	84	8	9.5
1900–1909	155	17	11.0
1910–1919	251	35	13.9
1920–1929	352	49	13.9
TOTAL	887	110	12.4

(Source: [12], Tables 1.1 and 1.2)

Table 5.2 Mathematics PhDs Awarded in the US, 1930–1989

Years	Total PhDs Awarded	PhDs to Women	Women as Percent of Total
1930–1939	780	113	14.5
1940–1949	735	87	11.8
1950–1959	2,325	109	4.7
1960–1969	6,407	363	5.7
1970–1979	10,877	1,086	10.0
1980–1989	7,356	1,159	15.6
TOTAL	28,480	2,917	10.2

(Source: [12], Table 1.2)

In light of that surprising development, I was especially eager to see how the Depression was reflected in the data, and to see how World War II and its aftermath created the "transition" Jeanne LaDuke had mentioned. Table 5.2 shows data, by decade, from the 1930s through the 1980s, the decade in which I earned my own PhD.

These data tell many surprising stories. First, the Depression didn't depress the number of mathematics PhDs as I might have expected, and the proportion awarded to women actually rose slightly. But the 1940s saw a decline in total PhDs awarded, reflecting the enormous impact of World War II on US higher education. By contrast, the spectacular growth in total PhDs awarded during the Fifties, Sixties, and Seventies reflects the equally spectacular postwar expansion of both higher education and scientific research. Set against this general backdrop, the patterns in PhDs for women are particularly striking. While women maintained a small but steady presence among the doctorates of the Forties, their decline as a proportion of total PhDs in the boom years of the Fifties and Sixties is startling in the extreme. In those years of Cold War expansion and economic growth, women PhDs in mathematics were a tinier percent of the total than they'd been since the 1880s. Indeed, it was not until the 1980s—when I was finishing up at Yale—that women's share of the doctorates reached and finally exceeded their 1930s levels.

The data for mathematics are part of a general pattern for US women in the sciences, one that the historian Margaret Rossiter has studied in detail [18–20]. Each rise and fall in the numbers and proportions of women tended to follow social, political, and economic trends, often with a slight lag time. The Depression, for example, seems to have had a generally discouraging effect on everyone, but that effect was likely greater for men. The war years certainly intensified this effect, only this time, as men went off to war, women were needed everywhere: in war-related industries, yes, but also on university campuses, where they worked as graduate students, instructors, and research assistants. But in the latter half of the Forties, the tables were turned, in a kind of Rosie the Riveter backlash: when the men returned from war, the women were expected to return home. The GI Bill, combined with the massive postwar expansion of higher education and federal funding for mathematical and scientific research, fuelled a tremendous increase in the number of math PhDs awarded, of which women received a tiny percentage.

A clash of countervailing forces gave rise to a gradual increase in women's share of the math doctorates into the Sixties and Seventies. As the Cold War continued, the demand for scientific and technological labor grew; new areas of research and development tended to be more welcoming to women, African-Americans, and other minorities. The movement for civil rights and racial equality gathered momentum in the Fifties and culminated in President Lyndon Johnson's signing of the Civil Rights Act of 1964. The Vietnam war and its accompanying protests had complicated effects on colleges and universities. In this general milieu of ferment and dissent, the movement for women's equality—part of second-wave feminism—grew apace. For women in mathematics, and university women more generally, the culminating event was Title IX of the Educational Amendments of 1972, signed by President Richard Nixon and intended to prohibit discrimination on the basis of sex in higher education.

The numbers in Tables 5.1 and 5.2 reflect these and a host of other fascinating social, political, and economic trends. Most notably, perhaps, from the perspective of the history of women in mathematics, they underscore one key fact: during the 100-year period starting in 1890, women earned over 3000 American mathematics PhDs—just over ten percent of the total. This fact is neither well-known nor well-appreciated. In the words of mathematician and scholar Cathy Kessel, when it comes to women mathematicians, "rumors of our rarity are greatly exaggerated" [10].

5.3 Documentary History, Oral History, Social History

Encountering this data in 1993, my first impulse was to attach as many names as I could to the roughly 200 women PhDs of the Forties and Fifties. Following the advice of Green and LaDuke, I began my search in the pages of the May *Bulletin of the American Mathematical Society* for the years 1941 through 1960. There, the AMS printed a nearly complete list of the previous year's Ph.D. recipients in the mathematical sciences, providing the first names of women but only initials for men, a fact that greatly simplified the task. I supplemented the list by consulting standard reference works, most notably *American Men of Science* (later known as *American Men and Women of Science*) and *Dissertation Abstracts*. These were the early days of the World Wide Web, which the Mosaic web browser had only just made accessible; so my research, like that of Green and LaDuke, began with physical reference books and microfilm in my university's library. I likewise used physical copies of the *Combined Membership List*, along with physical and microfiche phone directories, to find addresses, conduct surveys, and locate women for possible interviews.

In comparatively short order, I succeeded in compiling a rudimentary database on 188 of the women in my group. And I continued to tinker with it from time to time. But my primary, near-term goal was to meet and talk to as many of these women as I reasonably could—a task considerably simpler and more circumscribed than the one Judy and Jeanne were working on. In that pre-Internet era, they did most of their research by traveling: to college and university libraries and archives, Census Bureau offices, public records repositories, and cemeteries all over the US and Canada. They were doing the hard and necessary work of documentary history.

I chose instead a more manageable task: the collection of personal histories. I traveled around the country to meet and talk with 37 of the women, from whom I obtained 36 oral history interviews. (One of the women turned out to be in the early stages of Alzheimer's when I visited her in 1997. While I spent an enjoyable and interesting day with both her and her husband, it proved impossible for me to conduct a structured interview.) A handful of the women with whom I spoke were already well-known in the mathematical community and had been interviewed many times before. But for many if not most of the others, I was the first and perhaps the only person who'd really taken a sustained interest in their life and work. They entrusted me with stories that had never been public before.

The experience that brought this home to me most clearly arose from one of my earliest interviews, with Grace Bates (PhD, Illinois, 1946; 1914–1996), whose varied career as scholar and teacher extended from the mid-1930s to the late 1970s [2]. I realized only after we'd begun corresponding that she had, in fact, co-authored my high school algebra text, a valued book that's still in my personal library [9]. Bates agreed to meet me in June 1996 in her small apartment in the Pennswood Village retirement community outside Philadelphia, to which she'd moved 17 years earlier upon retiring from Mount Holyoke. There I met a delightfully opinionated, warm, candid, good-humored woman, in apparent good health despite nearly 60 years of smoking—a habit she explained, without apology, that she'd taken up while studying late at night for her master's degree at Brown (it helped her stay awake). She recalled, with some amusement, her own education and her many years of high school and college teaching. Although she never married, Bates said she'd always preferred the company of men. Indeed, one of the major downsides of having lived at Pennswood Village for so many years was that she'd outlived most of her male companions. "My problem," Bates confided, "is [that] I'm living too long"—but that didn't mean, she was quick to add, that she wanted to die. She didn't mind getting old as long as she could maintain her senses and her intellect. While she clearly loved her life, she also knew there were worse fates than death.

Over the next few months, Grace Bates—who said she'd never been interviewed at length before—worked with me by mail to finalize the interview transcript. I have, in my files, a copy of a letter, dated 4 November 1996, that I sent her to accompany the final version. Just two weeks later, on 19 November, Grace Bates died of a heart attack. I learned of her death in a letter from her niece, who had found my letter, along with the interview transcript, on her aunt's bedside table [1]. If, in fact, this had been the first-ever interview with this remarkable mathematician, it had also been the last.

It was another of my interviewees, Jane Cronin Scanlon (PhD, Michigan, 1949; born 1922), who first suggested to me that my project was a contribution to social history [3, 21]. In the main, the history of the American mathematical community has taken the form of hagiography, focused on the work of "giants" and "geniuses," nearly all of whom have been men. My emphasis, by contrast, was on gathering the stories of women in that community who, despite or perhaps because of the challenging circumstances under which they lived, were largely invisible to the hero-driven history of the discipline. And so I have come to see these oral histories as a step in the larger task of building a social history—an account of the lived experience—of American women in mathematics.

5.4 Back to the Database

I drew upon these oral histories to write a collective portrait of the 36 women, *Women Becoming Mathematicians* [12], published in 2000. When the book came out I knew that there was a larger project still waiting for me in the database. But other personal and professional matters seemed more pressing, and I took what turned out to be an extended hiatus from both mathematical and historical work.

Meanwhile, there were many exciting developments that profoundly affected the community of historians of women in mathematics. First and foremost, in my view, was the completion of Green and LaDuke's magisterial *Pioneering Women in American Mathematics*, published by the AMS in 2009 [7]. This book, together with its accompanying 674-page online supplement [8], is the culmination of their 30-year project to fully document the lives and careers of *all* the American women who received PhDs in mathematics from both American and European universities during the years 1886–1939. The quantity and quality of the information they present is nothing short of staggering. For each of the 228 women, they describe place, date, and circumstances of birth; early family life; places of residence; schools, colleges, and universities attended; jobs held; scholarly achievements; marriages and marriage-like partnerships; hobbies; social, political, and religious commitments; details of health and illness; circumstances of death.

My first (and enduring) response to *Pioneering Women* was awe and delight in Judy's and Jeanne's stunning achievement. My delayed response, however, was dismay: not at anything Jeanne or Judy had done, but at what I had not. My own database, sadly unfinished, seemed impossible to bring to anything approaching their degree of completion. And yet, I had long felt—and continue to feel—an essentially moral obligation to complete and publish this work. What to do?

Aside from *Pioneering Women*, the most relevant development in the decade or so since last I'd worked on the database was the explosive expansion of the Internet. Many of the kind of primary documents that Green and LaDuke traveled widely to see and touch are now available for inspection online. Genealogical records, census data, college bulletins and yearbooks, university archives, newspapers, journal articles, burial records—all are available on the open web, by university subscription, or via free or inexpensive online services. I realized that I could easily obtain a fuller picture of most, if not all, of my Forties and Fifties women from the comparative comfort of my own laptop. And so, over the past few years, interspersed with other writing and teaching projects, that's exactly what I've been doing: collecting information on each woman in the database and—most important—carefully documenting the sources I've found, reconciling inconsistencies, and double-checking details. My aim has been to get as close to primary sources as Internet access will allow. So, for example, much as I enjoy the Mathematics Genealogy Project (or MGP), the information found there is significantly "crowdsourced," and the supporting documentation is opaque to the user. I find myself supplying information to the MGP more often than the other way around [15].

While it's more like a charcoal sketch than an oil painting, the emerging portrait of the American women mathematics PhDs of the Forties and Fifties is intriguing in its broad strokes and small details. I have located a total of 192 women mathematics PhDs: 86 from the 1940s and 106 from the 1950s. The Forties women earned their PhDs from 28 different schools; the largest producers of doctorates were the University of Illinois (9), the University of Michigan (8), Catholic University (8), Harvard/Radcliffe (7), Chicago (6), and the University of California at Berkeley (6). With just one exception, all the Catholic University graduates were Roman Catholic nuns, accounting for seven of the 13 nuns awarded mathematics PhDs in the US in the 1940s. The one graduate of Catholic University who was not a member of a religious order was Euphemia Lofton Haynes (PhD, 1943; 1890–1980), now known to be the first African-American woman to earn a PhD in mathematics. There were, in fact, two African-American women to earn this distinction in the 1940s, the second being Evelyn Boyd Granville (PhD, Yale, 1949; born 1924), long mistakenly believed to have been the first. Curiously, both Granville and Haynes were born in Washington DC and had ties to Dunbar High School there, though they seem not to have been acquainted with one another [14].

Twelve of the 86 Forties PhDs were born outside the United States: eight in Europe, seven of whom left central or eastern Europe during the rise of the Nazis; three in Canada; and one in Palestine. Although fewer than ten of the women are still living, it's a generally long-lived group; the average lifespan of these women extended well into the 80s, and one, Esther Seiden (PhD, Berkeley, 1949; 1908–

2014) lived to the age of 106 [4]. All-in-all, at least 77 of these women had substantial careers, most of them in academia.

The slightly larger cohort of 106 Fifties women earned their PhDs from 42 different schools, the largest numbers coming from NYU (10), Brown (6), Michigan (5), Minnesota (5), and Illinois (5). Just one of the PhDs of the 1950s was African-American: Marjorie Lee Browne (PhD, Michigan, 1950; 1914–1979), whose degree was awarded within months of Evelyn Boyd Granville's. While 12 of the Fifties women were Roman Catholic nuns, only four of these earned their degrees from Catholic University, a striking contrast to the previous decade. Fourteen were born in Europe, many of them refugees from either Nazism or Communism; five were born in Canada and two hailed from the Asia/Pacific region. One of the European refugees, Halina Montvila (PhD, NYU, 1959; 1917–1997), seems to have been honored as Righteous Among the Nations at Yad Vashem, the Holocaust memorial in Jerusalem, having sheltered a Jewish man in Lithuania during the war [22]. As many as 25 of the women PhDs of the 1950s may still be living; the average lifespan of the 72 women who are known to have died was about 78 years. All told, at least 94 women—close to 90 percent!—in the Fifties group had well-documented careers, spread widely across academia, government, and industry.

I've thought long and hard about the appropriate medium for publishing the accumulated data, which currently exists in a collection of paper and electronic documents. In Summer 2016, I began constructing a website, womenbecomingmathematicians.net, which I plan to launch in Summer 2017. When the website launches, it will contain basic biographical data on all 192 women, which I will continue to expand and document after launch. The website will serve as both resource and work-in-progress, perhaps in a manner analogous to John J. O'Connor and Edmund F. Robertson's MacTutor History of Mathematics Archive [16]. The website may also, eventually, serve as a longer-term repository for documents, interview transcripts, and sound files associated with the collection of oral histories. Ultimately, of course, I'd like all these documents to find a permanent institutional home.

5.5 A Century of Doctorates

As recently as 2010, in a speech to incoming freshmen, then-Yale President Richard Levin stated matter-of-factly that no woman had earned a Yale PhD in mathematics until 1934 [13]. But in truth, the first Yale woman had done so nearly 40 years earlier; indeed, 1934 was the year of her death [14]. While President Levin kindly acknowledged his mistake, I and my fellow historians of women in mathematics couldn't help responding to this error with weary dismay. Such an egregious error only underscores the widespread misconception that female PhD mathematicians, are now—and long have been—few and far between.

But as we have seen, roughly 400 women earned PhDs in mathematics from American colleges and universities from 1886 through 1959. What's more, in the two decades that followed, more than three times that number accomplished the same feat! These statistics, and the names of the women behind them, should be a matter of well-known and established historical fact.

The sheer numbers of women earning doctorates in mathematics over time would seem to militate against a continuation of the kind of documentary history that Green and LaDuke have begun and I have tried to continue. But in recent years two mathematicians, Anne Leggett and Bettye Anne Case, have risen to the challenge. Illustrating just what an extraordinary amount of laptop-based research the Internet makes possible, they are well on the way to compiling a comprehensive database of the women mathematicians of the Sixties and Seventies [11]. Thanks to all our combined efforts, a century of women doctorates in mathematics is coming more sharply—and, with luck, more permanently—into view.

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Chapter 6
Excellence and Devotion: Black Women in Mathematics in the United States

Erica N. Walker

Abstract This reflective essay explores the rich history of Black women in mathematics in the United States, and their contributions to academe, research, and industry. Despite their significant activity in the field, Black women's contributions are often "hidden"—their work and research undervalued, their mentoring of others unacknowledged. This essay explores three interrelated themes—excellence, opportunity, and devotion—in the formative, educational, and professional experiences of Black women in mathematics. The essay concludes by exploring directions for future efforts to continue to build upon this group's incredible potential and achievements in mathematics. This chapter draws extensively from research conducted for and reported in the author's book about Black mathematicians, *Beyond Banneker: Black Mathematicians and the Paths to Excellence*, published by SUNY Press in 2014.

Keywords Black women • History • Mathematicians • Race • Gender

6.1 Introduction

This reflective essay explores the rich history of Black women in mathematics in the United States, and their contributions to academe, research, and industry. Despite their significant activity in the field, Black women's contributions are often "hidden"–their work and research undervalued, their mentoring of others unacknowledged. This essay explores three interrelated themes—excellence, opportunity, and devotion—in the formative, educational, and professional experiences of Black women in mathematics. Within the discussion of these themes, I analyze the unique position of Black women in a field still stratified by race and gender and trace historical events significant to Black women's interest and participation in mathematics. The essay concludes by exploring directions for future efforts to continue to build upon this group's incredible potential and achievements in mathematics.

E.N. Walker (✉)
Teachers College, Columbia University, New York, NY, USA
e-mail: ewalker@tc.edu

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6.2 Establishing a Tradition of Excellence

> It is instructive to consider the extraordinary determination to succeed by some African American women mathematicians born before 1950 who faced the additional challenges posed by racism [5].

The first Black women to earn their doctorates in the United States include Euphemia Lofton Haynes (1890–1980), Evelyn Boyd Granville (1924–), Marjorie Browne (1914–1979), and Vivienne Malone-Mayes (1932–1995). But it would be incorrect to assume that Black women had not pursued advanced study in mathematics before these women received their doctorates. For example, Anna Julia Cooper (1858–1964), most widely known as a civil rights and women's rights leader, earned her bachelors (1884) and master's degrees (1887) in mathematics from Oberlin College [6] and was a teacher and principal at the M Street School in Washington, DC. M Street, which later became known as Paul Lawrence Dunbar High School in 1916, was renowned for its excellent teaching staff and accomplished graduates. Cooper eventually earned a PhD in history in 1925 from the Sorbonne, the fourth Black woman in the United States in any field to earn a doctorate (and the first from the Sorbonne) [13, 22].

Dunbar must have been a special place—because two of the first three Black women to earn their PhDs in mathematics, Euphemia Lofton Haynes and Evelyn Boyd Granville, attended this school [32]. Lofton Haynes, the first Black woman to do so, earned her doctorate in mathematics in 1943 from Catholic University. Lofton Haynes' accomplishment as the first African American woman to earn her PhD in mathematics was unknown for many years, and in fact, Marjorie Browne (PhD 1950, Michigan) and Granville (PhD 1949, Yale) at various periods were each assumed to be the first African American women to earn their PhDs in mathematics.[1] Despite the fact that some reports published around the time of Lofton Haynes' death mention her receiving her doctoral degree in 1943, no one in the mathematics community seemed to have connected the dots until the late 1990s.[2] Granville, born and raised in Washington DC herself and a fellow alumna of Dunbar and Smith College, notes "[s]urprisingly, no one in DC ever mentioned the name of Euphemia Lofton Haynes to me and I did not hear about her until late 1999. This remains a mystery to me" [32].

Born in 1890, Lofton Haynes lived in Washington, DC, for much of her life—leaving only to earn her undergraduate degree in mathematics from Smith College in 1914 and a master's degree in education from the University of Chicago in 1920. Before leaving DC for Smith and the University of Chicago, Lofton Haynes

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[1] Browne finished the requirements for the doctorate in 1949, but it was not awarded until 1950.

[2] For additional information about Lofton Haynes, see Kenschaft's *Change is Possible: Stories of Women in Mathematics*. I thank an anonymous reviewer for noting that Lofton Haynes died just before the publication of Kenschaft's 1981 American Mathematical Monthly article, "Black Women in Mathematics in the United States," and thus, before Kenschaft and others could connect with her to include her in that work.

began her education in the segregated city schools of Washington, DC, attending what was then M Street School[3] and graduating from it as valedictorian [10]. A public secondary school in the nation's capital serving Black students, M Street's sterling reputation existed from the time of its founding as the Preparatory High School for Colored Youth in 1870 and in its later incarnations as M Street and Dunbar. (Dr Lofton Haynes later returned to Dunbar as the mathematics department chairperson.) From its beginning, this school was recognized for its excellence in educational opportunity and achievement. In segregated Washington, DC in 1899, for example, "in examinations given all high school students, the colored high school [M Street, at the time] scored higher than either the Eastern or the Western high schools [which were white]" [14]. As Alison Stewart writes in her book *First Class: The Legacy of Dunbar, America's First Black Public High School*, in the 1920s Dunbar's "all classical pedagogy focused on English, mathematics, the sciences, ancient history, Negro history, military drill, physical education, music, drawing, domestic science, Latin, Spanish, French and German" [30]. Dunbar and other segregated Black academic high schools of the era were staffed by administrators and teachers who often had earned advanced degrees, in many cases exceeding the qualifications of administrators and teachers at white institutions [17, 27].

While what made Euphemia Lofton Haynes decide to pursue her doctorate in mathematics is unknown, her commitment to education was clear. Teaching for 47 years in the DC public school system and also as a professor at Miner Teachers College in DC (now part of the University of the District of Columbia and where she established the mathematics department), she became a member of, and, eventually, president of the DC Board of Education. Widely acknowledged as a key proponent of integration in the DC schools in the 1960s and 70s, she was a fierce opponent of tracking in schools. She died in 1980, her status as the first Black woman to earn a PhD in mathematics largely unknown, leaving a substantial collection of her papers to Catholic University.

Many of the teachers at Dunbar, as Evelyn Boyd Granville attests and other chroniclers have described [7, 28], were highly educated and influenced their students to pursue postsecondary education. Lofton Haynes fondly remembered Miss Harriette Shadd, a teacher at Dunbar and a Smith College graduate—"I just idolized her, that's all" (Lofton Haynes oral history). It was due to Shadd's influence that Lofton Haynes wished to attend, and eventually enrolled in, Smith. When I interviewed Dr. Granville in 2009 for the book *Beyond Banneker: Black Mathematicians and the Paths to Excellence*,[4] she said the following about Dunbar [32]:

[3]Graduates of Dunbar (or M Street School, as it was first known) include luminaries such as Carter G Woodson, Charles Drew, and Mary Church Terrell.

[4]Benjamin Banneker (1731–1806) is widely acknowledged as one of the first Black "mathematical persons" in the United States. My book, *Beyond Banneker: Black Mathematicians and the Paths to Excellence*, based on archival research and in-depth interviews with thirty-five Black mathematicians who earned the PhD in a mathematical science, describes important formative, educational, and professional experiences of Black male and female mathematicians, as well as

> Dunbar gave us inspiration, quality education, and, you know, they made us feel good about ourselves...It was a tradition at Dunbar to encourage us to go to the Ivy League schools. And Miss Mary Cromwell [one of Granville's mathematics teachers] was the sister of Dr. Otelia Cromwell, a graduate of Smith in 1900, somewhere around there. Otelia Cromwell went to Smith, and then later went to Yale and got her PhD in English. And Miss Mary Cromwell and Dr. Otelia's niece [Adelaide] [7] also went to Smith. They encouraged me to apply to Smith, but I also applied to Mount Holyoke. And I was admitted to both Smith and Mount Holyoke, but I chose Smith, I'm sure at the urging of the Cromwells.

Other Black women mathematicians attending segregated schools before and during the Civil Rights era have reported similarly committed, highly educated teachers who were adamant that these young women excel in school and pursue postsecondary education [19, 21, 32]. Talented women, in general, were limited professionally to careers in teaching (and that was, for a time, only until they married). Talented Black women faced even greater odds against pursuing careers that allowed them to capitalize on their education and knowledge: in a different time, what else could Miss Harriette Shadd of M Street, Miss Mary Cromwell of Dunbar and numerous other Black women teachers who encouraged their students and provided high quality instructional experiences so that they would excel in mathematics have accomplished if given the opportunity?

Granville received her doctorate in mathematics from Yale in 1949, and then spent some time in New York City doing postdoctoral work at New York University. Eventually, she accepted a position at Fisk University in 1950, where she taught other Black women who became mathematicians, including Etta Zuber Falconer (PhD 1969, Emory University) and Vivienne Malone-Mayes (PhD 1966, University of Texas). Malone-Mayes commented that it was the presence of Granville that influenced her and others to pursue the PhD: No more than "six years older than the students she taught, [she] set high standards and demanded a quality performance from her students" [21]. Later in the 1950s and 60s, Granville began a career at IBM and NASA before returning to academe in 1967 as a professor in California and eventually retiring as the Sam A. Lindsey Professor of Mathematics at the University of Texas, Tyler. Asked once to summarize her accomplishments, Granville stated: " 'first of all, showing that women can do mathematics.' Then she added, 'Being an African-American woman, letting people know we have brains too' " [33]. Granville has received numerous honors, including honorary degrees from Smith College and Spelman College.

Lofton Haynes, Granville, Cooper, and others demonstrated excellence and did so in an era in the United States of race-based and gender-based stratification that suggested that women were incapable of scientific pursuits, and further, that sought to relegate Black women to manual labor [18]. Granville's quote—a familiar one to many Black women mathematicians—illustrates what has been called the "double bind" of being both a woman and a person of color in mathematics [25]. Despite their brainpower, Black women have struggled to find a place in the field,

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the unique historical and contemporary settings related to race, opportunity, and excellence that Black mathematicians experience.

and once there, their contributions have been sorely overlooked. Recently, attention has been deservedly given to Katherine Johnson and other women "computers" who were instrumental in facilitating the success of the early US space program [16, 26]. It is particularly gratifying that Katherine Johnson, a Black woman born in West Virginia in 1918, is the first female mathematician to be awarded the highest civilian honor in the US, the Presidential Medal of Freedom in 2015.

In Margot Shetterly's book *Hidden Figures: The American Dream and the Untold Story of the Black Women Mathematicians Who Helped Win the Space Race*, we learn of several Black women whose ingenuity and work was simultaneously undervalued and highly valuable, and whose career trajectories were thwarted because they were women, and because they were Black. Katherine Johnson, in particular, excelled at mathematics and other subjects throughout her educational career—indeed, she graduated from college at age 18 *summa cum laude* with degrees in mathematics and French. One of her professors at West Virginia State College, William Claytor (himself the third Black man in the US to earn his PhD in mathematics) recognized her talent and took it upon himself to ensure that she learned mathematics beyond the established curriculum. She became a teacher, and enrolled in a graduate program in mathematics (indeed, she was one of the first Black students to desegregate West Virginia University) but family commitments prevented her from completing a graduate degree. But then, as Shetterly powerfully writes: "It had always been Katherine [Johnson's] great talent to be in the right place at the right time" [26]. On a family trip in the early 1950s she learned about a mathematics job opportunity with the federal government in Hampton Roads, Virginia—at Langley Air Force Base. After a series of assignments within National Advisory Committee for Aeronautics (NACA)[5] programs, Johnson was key to the success of many of the Flight Research Division's projects, including the early spaceflights of Alan Shepard and John Glenn. Despite NACA's hiring of Black mathematics and science specialists, segregation was prevalent: for example, Black women were initially only assigned to the West Computing area of Langley, known as the "colored" computing section, and were expected to use segregated bathrooms. Johnson is one of many Black women whose stories are recounted in *Hidden Figures*—the documentation of their work exists, but has been obscured and overlooked.

These kinds of contradictions—Black women's contributions hidden in plain sight; opportunities for advancement and excellence circumscribed by a system of discrimination and inequality—are a prominent theme in the history of their mathematics pursuits in the United States. A host of factors, including their mathematical talents and interests, thwarted potential and the awareness of limited opportunity, the sense of being in the right place at the right time, the supportive and rigorous educational environment of their schools whether segregated or not, and the importance of family and community networks, all contribute to their varied paths to mathematics.

[5]NACA, founded in 1915, was incorporated into NASA in 1958.

These experiences shaped and formed these mathematicians, and, in turn, have inspired others to pursue mathematics. Their stories are largely overlooked reflections of American history, mathematics, and education across the 20th and 21st centuries. In many ways, their mathematical lives are metaphors for the Black experience in America—despite evidence of excellence, opportunities earned, granted, denied, rescinded; civil rights as citizens upheld as well as challenged; and an ever present "double-consciousness" [9] of what it means to be Black in educational and professional settings, and further, an ever present awareness of what has been called the "double-bind," "double knot," and "dual triumph" [5] of being Black and a woman in mathematics. Too often, it is a serendipitous moment that sets them on the path to achieving their full potential in mathematics. As Geraldine Darden (PhD 1967, Syracuse) recounted:

> I am not bragging, but I was a good student and was valedictorian of both my elementary and secondary graduating classes. I was the top student in my class in the Department of Mathematics at Hampton Institute. *Even so, nobody ever suggested that I go to graduate school in mathematics* [8].

Fortunately, in 1958, following increased national funding for math and science research opportunities after the Sputnik launch in 1957, Darden had the chance to study mathematics at a summer institute at North Carolina Central College. Upon her arrival, Marjorie Browne, a faculty member at Central, asked "Why aren't you in graduate school?" [7].

6.3 Opportunity in the Midst of Obstacles

> When you are both Black and Female, it is difficult to distinguish which of these traits may account for the way you are received by others. - Vivienne Malone-Mayes

The race and gender of Black women mathematicians have operated together to present unique opportunities for and obstacles to their mathematical development. US Black mathematicians, as members of an ethnic minority group within a small professional subset of individuals who are predominantly white and male often find themselves navigating largely white environments throughout their mathematical lives. For Black women, who are even more of a minority within the context of the professional community of mathematicians, these issues are magnified. In 2010, for example, only 9 doctorates (out of 863) in mathematics and statistics were earned by Black women [19]. In 2014–2015, of the 1901 new PhD holders in the mathematical sciences in 2014–2015, 880 of those (or 46%) were US citizens [31]. Of the US citizens earning the PhD, 20 were Black (10 Black women, 10 Black men) [1, 31].

But it should be noted that the Black women mathematicians interviewed for *Beyond Banneker* reported few gender-related obstacles to their mathematics progress during childhood and adolescence. As Vivienne Malone-Mayes (PhD 1966) stated about her school experiences in segregated Texas, "Black girls were expected to excel in their studies. No difference was made between boys and girls."

Indeed, when Black women mathematicians describe their learning experiences in school as children and adolescents, they largely describe classrooms in which girls are expected to perform as well as boys, and further, teachers who identified them as talented in mathematics and nurtured that talent [1, 2, 17, 32].

Further, when these girls grew up, expectations related to their gender certainly included marriage and motherhood, but for many of them, it also included working outside the home. As Malone-Mayes stated, "The moral lectures given by teachers and designed to stimulate students to aspire to high and lofty careers were directed equally to boys and girls. Every girl expected to work...Boys expected girls to work. Within our homes were working mothers" [21]. Indeed, it is important to note, that at least historically, "the African American community did not place as many restrictions on women as did the general culture" [5] in terms of gender roles in schools and professions. States Gloria Hewitt, the fourth Black woman to receive her PhD in mathematics: "Black women were always expected to work. The question was, at what?" [23]. One particularly moving story from *Hidden Figures* centers on Mary Jackson, a Black woman and award-winning NASA engineer, and her son, Levi. Working with his mother on his car's design, Levi entered a soapbox derby race in 1960 and won. He was quoted in the local Norfolk newspaper as saying "I want to be an engineer like my mother [when I grow up]" [26]. Mayes, the 5th Black woman mathematician to earn her PhD, said that within the Black community "girls were conditioned from my earliest recollection to prepare to work, [with the hope] that through education [they] could escape the extremely low paying jobs designated for Black women" [21].

The women mathematicians interviewed for *Beyond Banneker* reported that their gender was not an issue in terms of their mathematics pursuits in childhood and adolescence. In *Beyond Banneker*, one mathematician described her time in elementary and secondary school:

> Nobody ever made it seem like math and science should be hard, and so I think I just ended up doing well in it, because I didn't know it was supposed to be difficult or had to be difficult. But I think some people feel like it's just supposed to be hard or something, and I just never felt that way [32].

And for the most part, whether they earned their doctorates 10 or 60 years ago, there were very few instances of Black women reporting issues related to gender in their undergraduate experiences, whether those experiences were at historically Black colleges and universities or predominantly white institutions. One exception is particularly jarring, however:

> There was one really well-renowned professor at [my undergraduate institution] who basically told me, "Pick another major", because I was a math major when I first started out. I wanted to be a math major. I later found out from a white female post-doc [that] he was definitely sexist. She didn't even go into whether he was racist or not, but it definitely came out later that he was definitely sexist and he still thought math should be a male thing. That was the main reason I didn't major in math in college. I was 17 and impressionable, and here's this big name person telling me this, so I kind of believed it at the time [32].

Most women interviewed for *Beyond Banneker*, and many Black women mathematicians, reported that their gender became increasingly salient to how they were perceived as mathematics doers as they advanced through postsecondary education [15].

> Q: Did you feel any other times that you were isolated from others in mathematics?
> A: No, I don't think I ever did. I was really lucky. I don't think I ever felt isolated, because I had a group of friends—as I said, were in the AP classes [in high school] together, but even when we were in elementary school, we were all kind of...I don't want to say we were nerdy, but we all had an interest in math and science and all worked really hard. In college and grad school, I felt isolated, not because I'm not interested in math, but because I'm the only African American in the room, and sometimes the only female [32].

Graduate school can be particularly difficult for those who are underrepresented in graduate mathematics—women and members of ethnic minority groups [5, 15, 24]. If their ability in mathematics was not challenged before, as it had not been in high school or undergraduate studies, graduate school can become a kind of crucible for some mathematicians. This is undoubtedly true for many doctoral students, but for Black students, the overlay of race and perceptions of ability are vividly present in their descriptions of these experiences. For Black women, particularly those who attended HBCUs, it is often the first time that they are confronted with the "double knot" of race and gender—those who have low expectations of their mathematics ability because of their gender, and those who have low expectations of their mathematics ability because of their racial background. Malone-Mayes, attending her first graduate courses at the University of Texas in the 1960s, reported that she "was the only Black and the only woman. For nine weeks, thirty or forty White men ignored me completely. I never initiated any conversations as there was no encouragement to do so. It seemed to me that conversations before class on mathematics quickly terminated if it appeared that I was listening" [21]. One mathematician interviewed for *Beyond Banneker*, speaking decades after Malone-Mayes, reported:

> The women I know that went to big majority schools and try to be a math major get crushed. So the women in graduate programs tend to come from smaller schools. So forget about race, forget about gender, so maybe that's how they don't fit the successful graduate school package. Or coming from the South, you know, because people have all kinds of judgments about that. I mean, everything plays into it [32].

Another Black woman in graduate school in the 1990s took it upon herself to create study groups:

> So that first year I sent out this email and said that we were going to meet on Wednesday for lunch and then we were gonna work on our homework together in the library. And I just sent it to all the first year students. And people were like, "oh, okay". I mean like they were cool. Everybody showed up. We did that every Wednesday...And it really helped us to grow, but the only reason I did it was because I was like 'nobody is just gonna reach out to me to form a study group unless I form one myself'....It was so not official. It was just me deciding that I would rather we all work together so we could all learn from each other [32].

All of these experiences are challenging, and reflect that it requires more than mathematics talent to navigate graduate school. Now it is true that the women interviewed for *Beyond Banneker* are a select group who persisted in mathematics through the PhD, and so it is quite possible that Black women experience more acts of racism and/or sexism that discourage them from pursuing mathematics than are recounted by Black women who have been successful in attaining the PhD. But for these women, it is in graduate school where Black women seem to experience acts of sexism and racism.

Mathematics is still a field where a common trope about women in mathematics is that women cannot do mathematics at a high level, exacerbated by commonly recounted prejudices by people in the popular press, professors, and even a university president.[6] (Some female mathematicians report instances where they were encouraged to leave their doctoral programs despite passing qualifying exams, because “no one” was interested in working with them.) Less common nowadays, one hopes, is the supposition that women don’t “need” PhDs because their husbands will have one.

> The graduate chair called and gave me this nice, long conversation. He told me I didn’t need a Ph.D....That my husband’s going to have one and it would be too hard for both of us to get a job if we both had a Ph.D....I just dismissed him. I thought that was outrageous but I did not say anything there [32].

But there are still instances where Black women mathematicians feel that their gender is a problem for their colleagues and faculty at their graduate institutions. Among those interviewed for *Beyond Banneker*, Black women were more likely than Black men to mention the “graduate school switch”—earning the master’s at one institution, then finishing the PhD at another. All who mentioned this—male and female—pointed to acts of racism, either at the institution or within the department.

About her initial graduate school experience one mathematician noted:

> [That place] was traumatic. My self esteem took a beating. It was a very, very difficult time. The department was mostly comprised of white men who first of all did not feel like women could do math, let alone Black women, let alone a Black woman from a Black college. I just had too many strikes against me...That was one of the worst times of my life [32].

Her next graduate school experience was much more positive, largely due to the efforts of the department chair at the time:

> The department was bigger, so there was more [faculty diversity]. He [the department chair] made a concerted effort to really recruit Black students to the program, so there was a big network of Black students there at all levels so they could help each other as they went through the process...Even with the white faculty it was a different feel. I didn’t get that same sense of lack of belief in me. I think that grad school, in their minds, was a weeding out process for everybody, not just a select group of people. At [her first graduate institution], I felt like we were singled out. At [the second], they were like, “No. Grad school is hard. You’ve got to work hard.” I respected that and I planned to work hard. Just give me the chance to work hard. It was a different feel. It was a much better environment [32].

[6] Lawrence Summers, then President of Harvard University, made remarks about the potential for innate differences between women’s and men’s abilities to do science at a high level at a National Bureau of Economic Research luncheon in 2005. See, for example, http://www.harvard.edu/president/speeches/summers_2005/nber.php.

Black women are still a significant minority in graduate programs in mathematics, and as mathematics department faculty in most institutions.

> My graduate program was a culture shock. So, I was like the only woman and African American pretty much. In the first year class there were like 9 of us. There were three Hispanic guys, there was a Russian guy, two white guys, a couple Asians. I mean it was a very diverse group. But yeah, it was definitely different. I remember I would get called out when I would miss class because it was so noticeable. I mean it was just so obvious when I wasn't there because I was the only female and the only Black person. You know? I did feel like I stood out a lot more. It was just easy to notice if I was somewhere or not. The faculty were very supportive. I never felt like they didn't want me to succeed or anything. There was a Black woman who had graduated the summer that I started. And so I actually took her desk, took her office spot. But yeah, they were very supportive of African Americans. But it was just different. It was definitely a culture shock [32].

Etta Falconer, in her paper "The Challenge of Diversity" published in 1997, discussed several issues related to diversity in mathematics. In particular, she urges that "action must be taken to bring more women into the mathematics community as full partners and a few stars are not enough" [11]. In her continuing discussion of issues facing underrepresented people of color in mathematics, a section devoted to "the effect of culture shock" described the costs of being the only woman or person of color, or one of a few women or underrepresented persons of color in college or graduate mathematics. She noted that in predominantly white postsecondary environments "minorities must spend time and energy learning different patterns, values and behaviors" while "majority students can devote this same amount of time and energy to their studies" [11]. The feeling of being "singled out" relates to Claude Steele's description and analysis of how individuals (regardless of demographic background) respond to a perceived "spotlight" effect when they participate in activities where they are in the minority, and that can contribute to depressed demonstration of one's academic talent [29]. Steele calls this situational effect when one has the potential to confirm a negative stereotype about one's group, "stereotype threat," and it has been documented to have an impact on groups such as women in mathematics and African American college students. The impact of stereotype threat is most present for people who are strongly identified with the domain in question—that is, the impact of stereotype threat on mathematics performance could be particularly significant for women who consider themselves "math people."

Undoubtedly, Black women have experienced greater opportunities to pursue mathematics in education and as a profession in the United States over time. But there are still barriers, and it is sobering to think of women (the aforementioned teachers at Dunbar and other segregated schools, for example) whose opportunity to pursue advanced degrees and careers in mathematics was limited. Several mathematicians, male and female, in *Beyond Banneker* told vivid stories of thwarted talent within their families and communities. For example, Evelyn Boyd Granville recalled:

> I think my sister was good in math. But I don't remember exactly; I know she started college. But she didn't finish, she stayed one year and then she didn't finish. I don't know whether

> she was going to be a math major or not. I think she was pretty good. Now, my mother, I don't recall my mother being particularly adept at mathematics. And of course my mother didn't go to college, my father didn't go to college, so *I don't know what their real strengths would have been had they been living in this current situation, today* [emphasis mine] [32].

6.4 Dedication and Devotion

> I have devoted my entire life to increasing the number of highly qualified African Americans in mathematics and mathematics-related careers. High expectations, the building of self-confidence, and the creation of a nurturing environment have been essential components for the success of these students. They have fully justified my beliefs. Perhaps the most rewarding moments have come when younger faculty have undertaken the same goal and have surpassed my efforts, reaching out to the broader community to help minorities and women achieve in mathematics. - Etta Z Falconer, upon receiving the AWM Louise Hay Award in 1995

Throughout the narratives of Black women mathematicians shared in various essays, articles, and books, there is a prominent theme of devotion. Black women mathematicians exert influence and model successful practices in numerous ways—through their research, teaching, mentoring, program development, advocacy, and service. They are active in and have won awards for their research, teaching, mentoring, and service in professional organizations such as the American Association for the Advancement of Science (AAAS), Association for Women in Mathematics (AWM), Mathematical Association of America (MAA), and the National Association of Mathematicians (NAM), among others. In addition to the 1995 Louise Hay award bestowed upon her by the Association for Women in Mathematics, Falconer was elected a fellow of the AAAS and received its 2002 AAAS Mentor Award for Lifetime Achievement. Experienced women—whether they are those who have reached their career goals or those who may not themselves have accomplished all that they are capable of—support younger women who enter the profession after them. For example, Dorothy Vaughan, one of the first Black women hired as a mathematician at Langley, had worked as a math teacher. When not teaching, in wartime summers, she also worked in the laundry room at a military base in Virginia. As the West Computing section head at Langley, she mentored Katherine Johnson and numerous other women.

The extensive research on women's colleges demonstrates that women who attend these institutions thrive in terms of challenging stereotypes and experiencing success in their careers, particularly those careers in science, technology, engineering, and mathematics. Spelman College, founded in 1881 for the higher education of Black women, has been an exemplar in graduating women who go on to earn doctorates in STEM careers for decades. In fact, Spelman, on a per-student basis, "produces more African Americans who earn doctorates in the STEM fields than any college or university in America" [12].

As a physical space, the Albro-Falconer-Manley Building, also known as the "Science Building," on Spelman's campus has immediate visual impact. The Science Building is named for three women in the sciences (two of whom are Black American) with influential careers at Spelman: Helen Albro, Etta Falconer, and Audrey Forbes Manley. When one enters the building, the first thing one sees is an atrium with museum display cases, photographs, and other artifacts documenting the impressive history of women in the sciences at Spelman.

For Black women mathematicians in particular, including five Spelman alumni and professors who were interviewed for *Beyond Banneker*, the influence of Etta Falconer (1933–2002), who earned her PhD in mathematics in 1969 from Emory University, looms large over the science and mathematics programs at Spelman, as well as mathematics organizations and departments at other institutions.

Several mathematicians who are now college and university faculty spoke of Dr. Falconer's approach to insuring that students and alumni of Spelman were successful in their graduate science programs. One, Sylvia Bozeman, now retired from a distinguished career as a faculty member and administrator at Spelman, has won awards for her teaching and service to Spelman and the profession and was the first African American to be elected a Section Governor of MAA (in 1997 as the Southeastern Section Governor). Bozeman began her career as a mathematics instructor at Spelman and described Dr. Falconer's support for her completing the PhD and professional trajectory:

> You know, I had the best mentor for 30 years here at Spelman; Dr. Etta Falconer, and she was just incomparable as a mentor. So I came as really green, right out, with a master's degree. And so I just learned so much from her.
> She had the just most wonderful devoted following among all of us here in the sciences, because she didn't just mentor me, she mentored lots of faculty, lots of staff, and many more students. There were just lines of students outside her door all the time. Even her administrative assistant or secretaries, you know, they all went to school and left her. They all moved up. She mentored everybody [32].

A Spelman graduate who herself earned her PhD within the last 15 years was mentored both by Falconer and Bozeman, and, like others, also attributed Spelman's success in the sciences to Etta Falconer and her colleagues' lasting influence:

> Etta Falconer mentored me. I mean, she was the oldest person at Spelman, she was really responsible for this sort of renaissance of science at Spelman.
> And she was old school, she just kind of told you what to do, like, "You're going to present here," and, "You're going to do this," and, "You're wrong, you're right." So it wasn't a nurturing kind of mentoring, she just kind of told it [32].

These relationships continued long after students left Spelman. Graduates interviewed for *Beyond Banneker* reported that Falconer invited them to return to Spelman to speak to undergraduate majors about their careers, frequently gave advice at professional meetings, and encouraged them and supported the development of their research agenda. A Spelman graduate who is now a mathematician reported:

> Spelman was the first time I saw Black women with Ph.D.s in math, which I think has a very interesting impact. I think I only recognized it in hindsight because when I was there I sort of took it for granted. We had about five or six Black women on faculty that had Ph.D.s, and I just thought, "Oh, they're a dime a dozen." And it wasn't until my junior year that I

> realized there were fewer than 100 Black women who had ever gotten Ph.D.s in math. Not only that, to know that if I got one in five years I would still be in the top 100. It was just blasphemy [32].

An organization that focuses on the recruitment and retention of diverse women in mathematics, EDGE (Enhancing Diversity in Graduate Education), was founded by Sylvia Bozeman and her colleague at Bryn Mawr, Rhonda Hughes. EDGE brings small cohorts of diverse women entering graduate school together in the summers and provides mentoring (by EDGE alumni and faculty) year-round and for the duration of their graduate school careers and beyond [4] (also see chapter 20 in this volume). Several mathematicians (male and female) interviewed for *Beyond Banneker* have worked with EDGE, either participating themselves when they were graduate students as mentors and mentees, or teaching during the EDGE program. As one woman mathematician stated:

> That EDGE program is priceless. I cannot say enough positive things about what that program does and continues to do even with the cohort that we built. As we progressed, we still are in contact with each other. So it is helping even now at this level in my life [32].

Many Black women mathematicians through formal programs like EDGE or more informally through their everyday practice are deeply committed to increasing the participation of women and people of color in mathematics. Another former participant, now a university faculty member, stated:

> Probably, definitely the first important thing for me is this continuing to add more African American Ph.Ds and women to mathematics. Probably people will be saying that I am too young for this to be my most important thing, but because I was so influenced, I feel obligated to pass that on. So to get students excited about math and about deep math, that is my main focus. After that is probably the research. I know that if I can't keep it up, I can't pass it down because my advisor did not do research. [My advisor's] life is not quite fulfilled because of that. For me, I realized that that is something that I need to do [32].

Their dedication and devotion, however, can be a double-edged sword. Several mathematicians spoke about the significant service requirements (both at their colleges and universities and in the profession) that seem to fall disproportionately on Black women faculty. At times their extensive service is to the detriment of their health and career advancement.

6.5 Conclusion

The often hidden histories of Black women mathematicians in the United States reveal much about how they come to do mathematics in multiple contexts—home, school, community, college, university, and the profession, whether academe or industry. Although these mathematicians have varied paths to the profession, they share a common social and cultural bond—they are Black women in the United States.

While this is not to suggest that all African American women mathematicians have exactly the same experiences, there are significant commonalities. Too often, their paths to mathematics, despite their exhibited excellence, were in danger of being stymied for reasons of racism and sexism. In particular, younger Black mathematicians find themselves, still, at a curious intersection of race, gender, and opportunity. While opportunities are much more widely available for them than for those who came before them, they are still subject to sometimes hidden and sometimes stunningly explicit negative discourses about race, gender, and merit. Throughout their mathematical journeys, they may find themselves members of a very small group of Black students in mathematics classrooms in their high schools, colleges, and universities, and further, may have to address negative perceptions of their mathematical preparedness and expertise in graduate school classrooms. They ponder what happens to other students, who may be equally talented, whose parents may lack the advocacy skills needed to insure placement in advanced mathematics classes in schools, or to those who take the advice of professors that perhaps the mathematics major is not for them.

For many women, at critical transition points (graduating from high school to entering college as a math major; going from the undergraduate degree to graduate program; taking coursework and qualifying exams to completing the dissertation) there were gateways to mathematics that were provided by high school teachers and college and university faculty. Some of these moments could only be called serendipitous—in that there was great potential for these mathematicians to be overlooked as strong, or potentially strong, mathematics students. These doors could have easily remained closed, if not for Black women mathematicians who guided them, but also men and women of all backgrounds who championed them despite the prevailing rhetoric and practices that could have undermined their capability.[7] In 2000, three Black women, Tasha Inniss, Sherry Scott-Joseph, and Kimberly Weems graduated with their PhDs in mathematics from the University of Maryland [17]. They were the first Black women to do so from that department, and it was the first time that multiple Black women had earned their doctorates in one year from a university that was not an HBCU. They acknowledged that structures and practices of the department chairperson, Raymond Johnson, himself a Black mathematician, had created an inclusive, rigorous, and supportive environment [20].

Aside from the potential pitfalls of these critical transition points, there are some obvious examples of practices and policies that promote Black mathematicians' success [2, 3]. A common refrain in the narratives that older Black mathematicians share about their mathematical journeys is the importance of the 1957 Sputnik launch. The desire to best the Russians led to an unprecedented US investment in science, technology, engineering, and mathematics education at all levels. Increased funding for multiple types of programs for science, technology, engineering, and mathematics benefited many mathematicians, and especially Black and female

[7]For example, Lee Lorch has been discussed often as a strong supporter of African Americans in mathematics in general, and African American women in particular.

mathematicians. Mathematicians who were excellent high school students in math attended summer and Saturday STEM programs at universities and colleges; mathematics majors in college participated in summer research experiences funded by the National Science Foundation and were hired by faculty as research and teaching assistants under the auspices of professional development programs for minority mathematicians. Without this funding stream, it is possible that many mathematicians may not have had this exposure during that particular time period, when segregation was still prevalent. Indeed, the Black women "computers" and mathematicians at NACA and NASA are obvious beneficiaries of this moment in American history. This history and the increased participation of talented Black women in mathematics at that time speak to the value of continued and increased funding for such programs. But in a country that prides itself on being a place where every American can reach her God-given potential through hard work, we should not need such national imperatives to ensure access and opportunity to talented Americans, whatever their race or gender.

Too many talented math students in high school and college continue to be largely unaware of the opportunities that their mathematics prowess can bring them. Some of the women mathematicians whose stories are recounted here were largely unaware that they could go to graduate school for mathematics until quite late in their undergraduate college years. Quite a few "backed into" mathematics careers, with many assuming that they would be high school teachers or else, advised by well meaning teachers or adults, were steered into engineering or accounting. While there is nothing wrong with these careers, for some it was somewhat by chance that they happened to discover opportunities for graduate mathematics programs and that they, in reality, preferred the study of mathematics to other disciplines. In short, the pipeline to graduate study in mathematics does not start in college. Mathematicians and educators, whether they are in academe, industry, or government, should work to ensure that information and guidance about careers in mathematics are available to young people in secondary school or earlier.

Many Black women mathematicians are adamant about this mission to increase participation in mathematics, and thus take a long view of their work: they develop networks that persist long after students graduate from college, and the strong relationships between undergraduate faculty and alumni continue throughout their professional careers. They view their professional identities as encompassing not just their research and teaching, but also a "mission" to attract others to the field and the desire to "pass things on."

Black women mathematicians across generations have issued a call to action. And while they are convinced that mathematics as a discipline is a worthwhile endeavor, they acknowledge that practices and structures within the broader mathematics community do not necessarily support or invite Blacks into the field. However, they mentor others and craft environments and initiatives that facilitate the development of mathematics excellence for those who find existing structures unwelcome. Much of the work they do to bring others in the field is rooted in history and memory, and comprise deliberate practices to facilitate their own success and as well as the success of others. Too much of this work, which benefits many, irrespective of race and gender, is underappreciated and unrecognized.

Finally, there are too many stories of Black women's interest and excellence in mathematics that remain untold. These hidden stories, and the recently discovered histories of mathematicians like Euphemia Lofton Haynes, Katherine Johnson, and others, should make us wonder what we have missed learning about the people who know, love, and do mathematics. There are some who argue, strongly, that young people who exhibit keen mathematics talent will always be discovered and supported. The sheer number of potential missed opportunities to pursue and persist in mathematics for many of the mathematicians described here should counter that argument. It is up to all of us to ensure that we continue to identify and develop mathematical talent, whomever has it and wherever we find it, and that untold stories are shared, preserved, and not forgotten. Black women's mathematical talents are a "gift to the world"[8] and should be acknowledged as such. One hundred years from now, let us be able to see so many Black women mathematicians as to render their presence in the profession commonplace and unremarkable. Let us commit to ensuring that their excellence and devotion are rewarded with opportunity and inclusion.

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[8]The mayor of Atlanta, Kasim Reed, speaking at the inauguration of Spelman's 10th president in 2016, said that Spelman College "is a gift to the city, and to the world".

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Chapter 7
Founders, Feminists, and a Fascist – Some Notable Women in the Missouri Section of the MAA

Leon M. Hall

Abstract In the history of the Missouri Section of the MAA, some of the more interesting people who influenced the growth and development of the section through the years were and are women. In this chapter, we discuss the contributions of a few (certainly not all) of these women to the Missouri Section and mathematics as a whole, including Emily Kathryn Wyant (founder of KME), Margaret F. Willerding (who dealt with sexism in the 1940s), Maria Castellani (an official in Mussolini's Italy before coming to America), and T. Christine Stevens (co-founder of Project NExT). Without them, and others like them, both mathematics and the Missouri Section of the MAA would be poorer.

Keywords Mathematics • Missouri • MAA • Women • Myth • Staircase • Landing

7.1 Introduction

Women associated with the Missouri Section of the Mathematical Association of America (MAA) have had, and continue to have, meaningful roles in the mathematics community. Some of them founded organizations and programs still thriving today, such as Kappa Mu Epsilon and Project NExT. Although some might not have thought so themselves, they all were feminists to some degree, if only for being examples of women pursuing careers in a field dominated by men. Sometimes, those careers were curtailed or even ended because of the prevailing societal norms at the time. And yes, one really was a fascist, and held official positions in Mussolini's Italy before coming to the U.S. in the 1940s. We focus on a few (with apologies to all the deserving ones who were left out) of these women and their accomplishments, often achieved in spite of society's still-evolving ideas about what "a woman's place" should and should not be.

L.M. Hall (✉)
Missouri University of Science and Technology, Rolla, MO, USA
e-mail: lmhall@mst.edu

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Margaret Murray, in her 2000 book, *Women Becoming Mathematicians: Creating a Professional Identity in Post-World War II America*, [20], has introduced the idea of *the myth of the mathematical life course*, or briefly, *the myth*. According to the myth, an ideal mathematical career goes as follows. Extraordinary mathematical ability/potential appears early and is nurtured. A major in mathematics as an undergraduate is a foregone conclusion, and graduate school, the more elite the better, follows immediately after the bachelor's degree. Under the guidance of a respected mentor (who is further along in the myth), the doctoral dissertation makes significant contributions to an important area of mathematics. There follows a postdoctoral position and a tenure-track position at similarly elite institutions, and a productive research career while still relatively young gets well under way. At this stage, the person eats, sleeps, and breathes mathematics, and a spouse who effectively deals with the more mundane aspects of everyday life (i.e., everything not mathematics) is a great asset. With age, research slows some, but does not stop, and now being a mentor to those younger becomes more important. One is reminded of G.H. Hardy's prescription, "Young men should prove theorems and old men should write books." While the myth, or some of its main parts, has been around for a long time, Murray believes that the quarter-century immediately following World War II was a particularly fertile period for it to flourish. More pertinent to this paper, as Murray pointed out, the myth was applicable to and achievable by women only rarely, and always with difficulties not faced by men.

Indeed, few, if any, of the women discussed here had lives that even slightly conformed to the myth. For most, their mathematical life courses followed what we might describe in terms of a *staircase with landings*. (The *Escher Staircase* described by Jenny Harrison, [9], is a different way to use a staircase metaphor.) Academic ability, including but not necessarily restricted to mathematics, is recognized in high school or before, and a teaching career is envisioned. An early landing is teaching in a rural school, which was possible without a college degree in the first decades of the twentieth century. There was no specialization in mathematics or anything else in rural schools - all subjects, and usually all grades, were taught by one teacher. The next flight on the staircase leads to a bachelor's degree, which would allow access to the high school teaching landing. Now, specializing in mathematics begins to be possible. To enhance a high school career or allow access to the junior college landing, the master's degree flight may be climbed. If, during the bachelor's and master's work, sufficient mathematical aptitude is shown, a doctoral program might be pursued; however, a doctorate in mathematics only becomes a goal late in the process, unlike in the myth, where it is there from the beginning. After the doctorate, college and university landings are accessible, research positions become possible, or the person can return to lower landings, such as high school. Each landing can be viewed as both an exit from the staircase and an entrance to a career, and the staircase may be reentered as many times as desired. The women we consider here all reached the doctorate landing.

The staircase was littered with additional obstacles for women, though, which have not been completely cleaned up even today. A big one was, especially in the first half of the twentieth century, for women, the words "marriage" and "career" were usually connected by "or," not "and." Most workplaces, including schools and colleges, had either explicit "anti-nepotism" rules or long-established customs against employing married women, especially married women whose husbands were employed at the same place. Part of the rationale was that a married woman should be supported by her husband and thus should not "take away a job from a man." One can imagine the doors to all the opportunities at all the landings slamming shut for her as a bride said, "I do." This mindset persisted well into the mid-twentieth century in many places, and some of today's women (and men, too) in mathematics are unaware of it. This represents progress, but to get some perspective, they could read Patricia Kenschaft's *Change is Possible: Stories of Women and Minorities in Mathematics*, [13]. Kenschaft recalls her own experience in the 1960s or 1970s of being offered a job teaching mathematics at a liberal arts college, but then two days later getting a call from the department chair, who said, "A young man just stopped in my office. He really *needs* a job, so I gave him yours. I'm sure you understand." We shall see how some of the women we discuss dealt with combining marriage and a career, and how doing so gradually became accepted by society.

Of course, we need to be careful about indiscriminately applying metaphors to any particular person's career, realizing that both men and women mathematicians have achieved their career goals in a variety of ways; but the myth and its mindset have real influence, and the staircase is well worn.

7.2 Eula Weeks-King

Eula Adeline Weeks (Figure 7.1) was from Rich Hill, a small town in western Missouri about halfway between Kansas City and Joplin. Her family had moved to Missouri from Georgia a little before 1900. In 1901, at age 19, she was a teacher in the Rich Hill high school. She entered the newly founded Teachers College at the University of Missouri (refers to the Columbia campus, unless otherwise designated), and in 1908 received both a BA and a BS in education. Weeks was valedictorian of the Class of 1908 in the College of Arts and Sciences at Missouri. She continued at Missouri as a university fellow in mathematics and earned a master's degree in 1909. After spending three years at Bryn Mawr, she returned to Missouri where she completed her mathematics Doctorate in 1915, with a dissertation titled *A Symmetrical Generalization of the Theory of Functions*. Her advisor was Earle R. Hedrick. She was Hedrick's first and only doctoral student, the first woman to get a doctorate in mathematics at Missouri, and the second person overall to get a doctorate in mathematics there, [28]. We can only speculate why Weeks returned to Missouri for her doctorate and did not get it at Bryn Mawr. Maybe she failed the qualifying exam; maybe Charlotte Angas Scott, who was the advisor or co-advisor for six of the first seven mathematics doctorates (through 1920, one advisor is unknown) at Bryn Mawr would not take her as a student; maybe the plan all along was to go back to Missouri and work with Hedrick.

Fig. 7.1 Eula Weeks in 1908 (reproduced from the University of Missouri yearbook, *The Savitar*)

Following her doctorate, Weeks became a teacher at Grover Cleveland High School in St. Louis. Given her connection to Hedrick, a prime mover in the creation of the MAA and its first president, it is no surprise that she was a charter member of the MAA and its Missouri Section. However, her main professional activity was with the National Council of Teachers of Mathematics (NCTM). Her principal nationwide service to mathematics was as a member of the National Committee on Mathematical Requirements. This five-person (initially) MAA committee was appointed by President Hedrick in 1916, with J.W. Young of Dartmouth as chairman and members A.R. Crathorne, Illinois, E.H. Moore, Chicago, D.E. Smith, Columbia, and Oswald Veblen, Princeton, [10]. The committee formulated its own charge based on the following questions, [11]:

1. What general educational values (utilitarian, disciplinary, cultural) can actually be secured by the study of mathematics?
2. What should be the primary purposes of mathematical instruction?
3. What topics and what treatment of these topics will best serve to realize the values and purposes under (1) and (2)?
4. How much of the content included under (3) should be required (a) of all students in secondary schools; (b) for college entrance; (c) of all students in college?
5. What should be the preparation of teachers in secondary schools and in colleges?

Because this list included considerations of secondary school mathematics, the committee requested that some of the regional mathematics teacher organizations appoint members to augment the committee. The committee also was authorized to add other members as it saw fit and the need arose. The committee operated for eight years, and its final report of more than 650 pages, *The Reorganization of Mathematics in Secondary Education*, [21], was the most comprehensive work on the teaching of mathematics in the U.S. up to that time. For more, see Section 6 of [29].

Weeks was added to the committee in the fall of 1919. At the time, she was also a member of a special commission appointed by the College Entrance Examination Board to report on college entrance examination requirements, and this could have been a reason she was asked to join the committee. The two positions were a natural fit - one chapter of the committee's report, [21], dealt with college entrance requirements and another with standardized tests in mathematics. Weeks was a member of the subcommittee appointed to prepare a report on elective courses in mathematics for secondary schools, and was active in publicizing the work of the committee in the Midwest. She spoke on this topic at two Missouri (November, 1920 and November, 1921) and one Kansas (January, 1923) MAA Section Meetings, and at a summer Mathematics Club meeting at the University of Illinois in 1922. In addition, she was Vice President of the NCTM during 1922–23 and a member of the NCTM Board of Directors from 1923 to 1926. Locally, she was a member of the Missouri Society of Teachers of Mathematics and Science, serving at least one term as secretary.

In 1924, Eula Weeks married Harry Lane King, another teacher at Grover Cleveland High School, essentially ending her professional career. At this time, many school boards had established policies that married women were not to be employed as teachers, and so, after her marriage, Weeks-King resigned her teaching position. If she had not resigned, she almost certainly would have been dismissed. This issue faced other women in mathematics into the mid-twentieth century. Neither pursuing the myth nor climbing the staircase is worthwhile if you can't get a job. Weeks-King did maintain her MAA membership until at least 1938 and continued on the NCTM Board for two years after her marriage. She also attended the twentieth Annual Meeting of the MAA, held in St. Louis in 1935.

Eula Weeks-King continued to live in St. Louis until 1967, when, now alone after her husband's death the year before, she moved to her son's home in California. She died later that same year at age 84.

7.3 Emily Kathryn Wyant

The first woman officer in the Missouri Section of the MAA was Emily Kathryn Wyant (Figure 7.2); she was Chair in 1927. Wyant was an Instructor at Missouri from 1921 until 1930, and worked on her doctorate during this time, finishing in 1929. Her dissertation was *The Ideals in the Algebra of Generalized Quaternions over the Field of Rational Numbers* and her advisor was G.E. Wahlin. In 1930, Wyant left Missouri for Northeastern State Teachers College in Oklahoma, and in 1934, she became the mathematics department chair at Athens College in Alabama.

Fig. 7.2 Emily Kathryn Wyant in 1921 (reproduced from the University of Missouri yearbook, *The Savitar*)

While at Missouri, in addition to her involvement in the MAA, she was quite active in the mathematics honor society Pi Mu Epsilon. At that time, Pi Mu Epsilon had become the national society for instructors and advanced students at universities with graduate programs. After moving to Oklahoma, Wyant, with the support of her department head, envisioned a national mathematics society for undergraduates, and in 1931 transformed the local mathematics club into the first chapter of Kappa Mu Epsilon, the mathematics honor society for schools that emphasize undergraduate education. Changing the name of a local club is one thing, but the creation of a national organization is something else altogether. Wyant wrote many letters to colleagues at other undergraduate institutions, and by the end of 1932, there were six chapters in five states.

She was the first national president of KME. For more on the history of KME, see the "History of KME" link, [4], on its website. The current KME national president (through April of 2017) is Rhonda McKee, University of Central Missouri, who is an active member of the Missouri Section of the MAA. The end of her term as president will close a seventeen-year stretch of service as an officer of KME.

Wyant's doctoral work at Missouri included one summer at the University of Chicago, and she did postdoctoral work there in 1933–34, between her positions in Oklahoma and Alabama.

Unfortunately, not long after moving to Alabama her health began to fail, forcing early retirement in 1940 at the age of only 43.

Even as her physical condition deteriorated, Wyant made remarkable efforts to keep up with KME activities. According to her obituary, [23], in *The Pentagon*, KME's official journal,

> During the next few years, Dr. Wyant watched every step that Kappa Mu Epsilon took. She corresponded with the officers although her hand was too feeble for her to actually write the letters. Many remember her amazing trip with the aid of a nurse from Athens, Alabama, to Warrensburg, Missouri, in order that she might attend the last national convention.

That convention was in April of 1941. Wyant died fifteen months later, in July 1942.

7.4 Nola Anderson Haynes

A contemporary of Wyant's (they were the same age) as a student at Missouri was Nola Anderson (Figure 7.3) (later Haynes), who also earned her doctorate there in 1929; her dissertation was *An Extension of Maschke's Symbolism* and her advisor was Louis Ingold. Like Wyant, she participated in the Missouri Section of the MAA while working on her doctorate and left Missouri afterwards. Unlike Wyant, however, Anderson-Haynes came back to Missouri and had a long career there. She is a good example of someone who climbed the academic staircase with stops at several landings, as did Weeks and Wyant. Anderson taught at a rural school before receiving her BS degree from Missouri, and after her degree taught two years at the high school in St. Charles, Missouri, plus one year at Central College for Women, a two-year college in Lexington, Missouri. Aiming at a career teaching at a junior college, she went back to Missouri in 1925 to get a master's degree in mathematics and astronomy. As related in Judy Green's and Jeanne LaDuke's *Pioneering Women in American Mathematics: The Pre-1940 PhDs*, [6], after completing her master's, the department chair, W.D.A. Westfall (part of the Hilbert - Missouri connection, see [28]), offered her a fellowship to continue towards a doctorate, an offer she accepted instead of seeking a junior college position.

After her doctorate, with now-widened career options, Anderson taught as an Instructor at Missouri for one year, and then in 1930 joined the faculty of H. Sophie Newcomb College, a degree-granting institution for women that was part of Tulane, in New Orleans, as mathematics department chair. While there, she was active in the Louisiana-Mississippi MAA Section, serving as both secretary and vice-chair. Early in her career, she did more than teach. Her doctoral dissertation was published in 1929 in the *American Journal of Mathematics*, and the same year she had an article, "The trigonometry of hyperspace," published in the *American Mathematical Monthly*. Later, in 1936, she and Ingold got their paper, "Normals to a space V_n in hyperspace," published in the *Bulletin of the American Mathematical Society*.

In 1938, Nola Anderson married E.S. Haynes (who was seventeen years older than she), chairman of the astronomy department at Missouri, who had been a member of her doctoral committee. Haynes' wife of twenty-five-plus years had died in 1934 and he had two adult sons. Returning to Missouri, Anderson-Haynes fully expected her marriage to mean the end of her academic career, as it had for Eula Weeks-King's, due to the similar strict nepotism policy then in force at Missouri. Rules and policies were changing, though, and her timing was good. Because of

Fig. 7.3 Nola Anderson in 1922, and Nola Haynes in 1996 (reproduced from the University of Missouri yearbook, *The Savitar*, and the UM Mathematics Department newsletter, *Critical Points*)

the shortage of instructors to teach during World War II and the big influx of G.I. Bill students afterwards, she was hired by the Missouri mathematics department in the early 1940s. However, things had not changed completely. Her job titles always included the word "acting" before she was given a regular academic appointment as associate professor in 1951, the year after her husband retired. Apparently, after acting like a regular professor for nearly ten years, she finally actually got to be one. In Missouri, Haynes continued her involvement with the MAA, serving two terms, from 1951 to 1952 and from 1960 to 1961, as secretary-treasurer of the Missouri Section and one term, from 1963 to 1964, as chair.

Nola Haynes died in December of 1996, less than three weeks before her hundredth birthday. More details about her life and career can be found in [6], [19], and [28].

7.5 Margaret Willerding

Margaret F. Willerding (Figure 7.4) was quite active in the Missouri Section from 1948 through 1956, attending every meeting in those years. While working on her doctorate at St. Louis University in the 1940s, she supported herself as a teacher in the St. Louis public schools. She finished her doctorate, with advisor Arnold Ross, in 1947 with a dissertation titled: *Determination of All Classes of Positive Quaternary*

Quadratic Forms which Represent All (Positive) Integers and accepted a position as Instructor at Washington University that fall.

During 1946–47, Ross had moved to Notre Dame, and Willerding spent much of that year commuting, most likely by train, between St. Louis and South Bend on weekends while finishing her dissertation. In South Bend, she became acquainted with Eugene Guth, a Hungarian theoretical physicist who was a friend of Ross. She and Guth were briefly engaged to be married, but Willerding did not go through with it. The fact that Guth was considerably older than she was could have played a role. Also, although she was trained as a research mathematician, and probably could have been a good one, Ross and Guth were the only research mathematicians she knew much about, and, as she recalls in an interview with Murray, [20], “All they did was eat, drink, and sleep mathematics, and I said, ‘There’s more to life than this.”’ Ross was department chair at Notre Dame, and was interested in hiring Willerding to create a research group of himself, her, and Guth, but it was not to be. Had she married Guth and gone to Notre Dame, Willerding, who had spent time on the public-school-teaching landing of the staircase, might have been able to realize something fairly close to the myth. She didn’t lack self-confidence, telling Murray in [20], “If I could have gone to Bryn Mawr and studied with Emmy Noether, I might have been quite a famous mathematician now.” On the other hand, she might have found herself expected to play the supportive spouse role for Guth’s pursuit of the physics version of the myth (which he came close to achieving, see [7]). Anyway, especially given her remark above, the myth didn’t seem to be something Willerding saw as all that desirable, and she sure wasn’t about to conform to someone else’s myth.

This experience did not turn her away from a research career, though; her position at Washington University carried research expectations with it, and she got her dissertation published in the *Bulletin of the AMS*, a good start. However, as she related in [20], she began to feel that Washington University was not a place where she could prosper. For one thing, the department head told her when she was hired that she should not expect to be promoted as fast as a man, even if she did as much or more work than her male colleagues. Another incident was connected with the AMS Regional Meeting held at Washington University in the fall of 1947. There was a tea for the participants on Friday afternoon of the meeting, and one of the faculty wives called Willerding to ask if she would pour at this event. Her answer was, “I don’t intend to pour at one of the teas you’re having. I’m one of the *faculty*.” After just one semester, she had had enough and resigned her position at Washington University.

Because Willerding had previously taught for the St. Louis school district, she was able to request reactivation and to be assigned to the faculty at Harris Teachers College in St. Louis, her undergraduate alma mater. This marked the beginning of her transition from a pure mathematics research career to one in mathematics education, where she was very successful. She was the author of over 30 textbooks. She was the second woman (after Wyant over 20 years before) to hold an office in the Missouri Section when she became Secretary-Treasurer from 1949 to 1950, and from 1952 until 1956 she served as the Association Secretary. Beginning in 1952 there were two secretaries for the section, a Local Secretary who presumably handled correspondence and other details pertaining to the section meetings, and

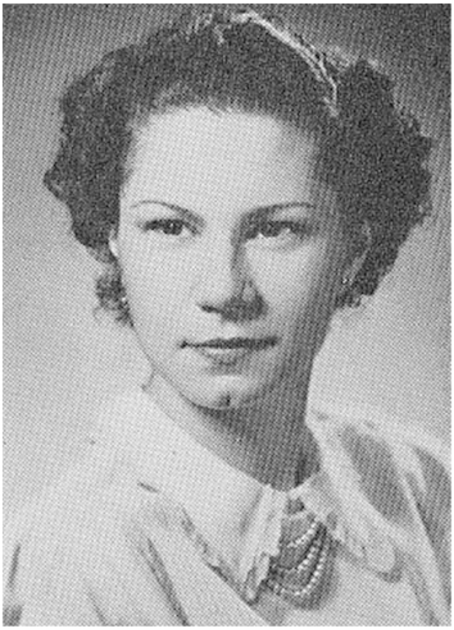

Fig. 7.4 Margaret Willerding in 1949 (reproduced courtesy of Harris-Stowe State University Archives)

an Associate (or Association) Secretary, who was the person who dealt with the national MAA. Willerding was elected Associate/Association Secretary in 1952, and in 1956 she was re-elected Association Secretary for a period of another five years [27]. When she left Harris Teachers College and Missouri for a position at San Diego State College in the fall of 1956, the position of Association Secretary was not re-filled.

In June of 1954, Willerding became editor of the Mathematics Problems Department of the journal *School Science and Mathematics*, succeeding another member of the Missouri MAA section, Prof. G. H. Jamison from Northeast Missouri State, in this post. Jamison had been editor of the Mathematics Problems Department since 1931, and Willerding did the job until 1976. The following story [16] not only sheds light on Willerding's personality, but also illustrates the culture women had to deal with, even from their friends, in both mathematics and society in the mid-twentieth century.

George Mallinson was the editor of *School Science and Mathematics* during most of Willerding's time as problems editor there. He was Dean of the School of Graduate Studies at Western Michigan University, and became editor in 1957. He and Willerding had never met, but he was pleased with her handling of the Problems Department. Then, in the early 1960s, at a meeting of NSF Institute Directors, Mallinson met someone from San Diego State and asked about Willerding. The person said that he didn't know her well, but thought she was a nice person, a good teacher, and "of rather advanced age." At the time, Willerding was in her 40s, which even then could hardly be considered "of advanced age," but that remark worried

Mallinson a little because he recognized the value to the journal of the problems department and didn't want to break in a new editor for it in the near future. So on a trip to California a couple of months later he arranged a meeting with Willerding. She was to pick him up at his motel, and they would have a dinner conference. As Mallinson recalls in [14],

> At about 6:00 PM on the meeting date, a rap was heard at the door and [I] opened it and was very astonished. Before [me] was a very svelte, well-constructed young lady in a perfectly fitting dress, dark hair drawn back, standing in front of a robin's egg blue Thunderbird. [My] first thought was that the young lady had not come to the right room. That thought was dispelled when she laughed and said, "So that's what in h____ a dean looks like!"

They had a pleasant dinner, Mallinson's concerns evaporated, and Willerding continued her very capable and professional editing of the *School Science and Mathematics* Problems Department until 1976. When she did step down as Problems Department editor, she was ready with a recommendation to Mallinson, who was still editor, for her replacements (she was replaced by two men). He took her advice.

Murray interviewed Willerding in person for [20], and that reference contains more details and insights about her life and career. Willerding died in San Diego a few years later, in 2003.

7.6 Maria Castellani

Maria Castellani (Figure 7.5) was at the University of Kansas City (now University of Missouri Kansas City) from 1946–1961, serving as the mathematics department chair from 1951–1961, and holding the Lena Haag Chair in Mathematics beginning in 1957. She was active in the Missouri Section of the MAA and was section chair in 1955, the second woman to hold that office. Castellani received the doctorate in Mathematics at the University of Rome in 1923, and spent 1923–24 at Bryn Mawr as the Italian Scholar in Mathematics. Neither her advisor's name nor her dissertation title has been found. In [12], she is identified (during her time at Bryn Mawr) as "assistant to Professor Castelnuovo of the University of Rome," but she is not among the students of Castelnuovo listed on the Mathematics Genealogy website. Her 1925 paper in the *Transactions of the American Mathematical Society*, "Algebraic surfaces with reducible bitangent and osculating hyperplanar sections," likely was based on her doctoral work.

Castellani's life did not conform to either the myth or the staircase model. She had an interesting and varied career in Italy before moving to Kansas City, where the U.S. academic mathematics phase of her life began in middle age. After returning from her year at Bryn Mawr, she became head of the League of Nations' Accounting Office in Geneva. This post, along with her many contacts abroad (relative to Italy), made her a natural choice to be named president of the Mussolini regime's *Associazione Nationale Fascista Artiste e Laureate*, or ANFAL (which translates as National Fascist Association for Women Artists and Graduates). One of the

Fig. 7.5 Maria Castellani circa 1930, and at the University of Kansas City in 1947 (reproduced from (http://www.fondazionefidapaonlus.it/wp-content/uploads/2013/05/ANNULLO-X-I-25-ANNI.jpg), and the University of Kansas City yearbook, with permission of University Archives, University of Missouri – Kansas City)

organization's founders, Castellani led ANFAL throughout the 1930s. It was not an easy job, and to be an effective advocate for women in Mussolini's Italy must have required a high degree of political astuteness. Challenges she faced ranged from preventing mass movement of women workers from rural areas to the cities (an effort that was never very successful) to providing women for traditionally male occupations in order to free the men for frontline military duty. Involvement in politics was unavoidable. For example, see Victoria De Grazia's *How Fascism Ruled Women: Italy, 1922–1945*, [1], for details of the conflict between ANFAL and a rival Italian women's association, FIDLIS, the organization of Italian women degree holders.

During this time Castellani was actively involved with the International Federation of Business and Professional Women (BPW), and was the prime mover in founding the Italian branch, *Federazione Italiana Donne Arti Professioni e Affari*, or FIDAPA. She spoke at the July 1933 International Federation of Business and Professional Women Congress, held at the Palmer House in Chicago. In the press release for this event, carried by many U.S. newspapers, she was described [22], by: "The Fascist viewpoint will be presented by Dr. Maria Castellani, manager of the statistical bureau of the largest insurance institute in Italy, first woman to become a bureau chief under the Mussolini regime." Through her International BPW activities and her involvement in broadcasting, she became internationally known. In 1936, she hosted a radio broadcast from Italy, which was heard nationwide in the U.S. on NBC [17], featuring Maria Cristina Marconi, second wife of Guglielmo Marconi, the Italian inventor and Nobel Prize recipient. The topic of this show, "The Status of Women Under Fascism," was not scientific. Considering Castellani's experience in broadcasting, it should be no surprise that when she was Chair of the Missouri Section of the MAA, the invited speaker that year, Philip S. Jones from the University of Michigan, spoke on "The Use of Television in Mathematics Education." One wonders whether Jones realized that his hostess probably knew more about his topic than he did.

Her government service did not prevent Castellani from also teaching and doing mathematics. According to [24], she had over 100 published studies and research, scientific and actuarial, before coming to America, and she wrote other, non-technical pieces, including a book titled *Italian Women Past and Present*. However, her career in Italy was ended in 1940, possibly because she was a woman, possibly because of her ethnicity, possibly both. Considering her decade and a half of service to her country, this was nothing less than betrayal by her government. In 1938, some say mainly to appease Hitler, Mussolini enacted racial laws that restricted civil rights of Jews, in particular excluding them from public office and higher education. Castellani was suspended from her government posts and from the university in 1940 [24]; later that year she came to America. In [1], De Grazia notes that in 1938 the last surviving organizations that had tried to reconcile fascism and feminism in Italy, of which ANFAL was certainly one, were disbanded and their Jewish members banished from public service. (This makes the above 1940 date from [24] less certain.) Specific evidence that Castellani was Jewish has not been found, but it is strongly suggested by the statement in [24] that the racial laws were responsible for the loss of her positions.

While at the University of Kansas City, in addition to being active in the Missouri Section of the MAA, Castellani published one paper in the *Annals of Mathematical Statistics* and supervised eleven master's theses (see [2]). During this time, she also published at least one monograph on statistics through the Mathematical Institute of the University of Rome. In 1961, she was hired as Mathematics Department Chair at Fairleigh Dickinson University in New Jersey, where she spent the rest of her U.S. career. After retirement, she returned to Italy and again was active in FIDAPA. She died in Rome in May 1985. Richard Delaware of the University of Missouri Kansas City maintains an informative department-history web page, [2], with a section devoted to Castellani.

7.7 MAA Award for Distinguished Service to Mathematics

The MAA's Award for Distinguished Service to Mathematics was first presented in 1962, and the Gung and Hu Award for Distinguished Service has been its endowed successor since 1990. This is the most prestigious award for service given by the MAA. We close with the three women from the Missouri Section who have received this award. They represent one-third of all women recipients, and all the Missouri Section recipients.

7.8 Shirley Hill

Shirley Hill (Figure 7.6) climbed the mathematical staircase; following her bachelor's degree from Missouri in 1948, she taught in Kansas City schools and got a master's from the University of Kansas City in 1956 before going to Stanford where she received her doctorate in 1961. Her advisor was Patrick C. Suppes, and her dissertation was *A Study of the Logical Abilities of Children*. She co-authored a well-regarded textbook, *First Course in Mathematical Logic*, with Suppes in 1964, and in 1970 co-authored *Elementary Geometry* with Vincent Haag and Clarence Hardgrove.

Hill focused her career on teacher education and curriculum development, and was a strong advocate for public support of education by attending congressional hearings, talking with legislators, and cultivating relationships with other organizations to influence the world of mathematics education. She played important roles both on policy boards and on curriculum development projects, often being selected as the leader, and has thus influenced mathematics teaching and learning at all levels and in many countries. This activity began at Stanford, where she was the assistant director of the Stanford University Arithmetic Project. In the 1970s, she chaired the National Advisory Committee on Mathematical Education and was a principal author of its report, *Overview and Analysis of School Mathematics K-12*. She was elected president of the NCTM for 1978 to 1980, and strongly influenced the NCTM publications *Curriculum and Evaluation Standards for School Mathematics* and *Agenda for Action*. She was influential in the formation of the Mathematical

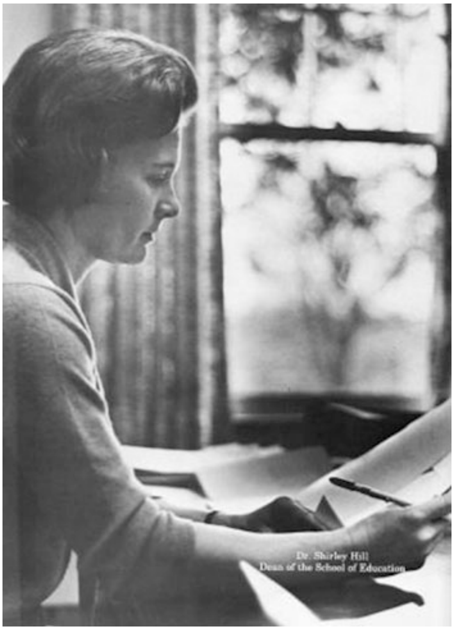

Fig. 7.6 Shirley Hill in 1965 when she was Dean of the UMKC School of Education (reproduced from the UMKC yearbook, with permission of University Archives, University of Missouri – Kansas City)

Sciences Education Board and was its chair from 1985 through 1989, during which time the project *Everybody Counts* was developed. Hill received the MAA's Gung and Hu Award for Distinguished Service in 1991, and was the inaugural recipient of the Mathematics Education Trust Lifetime Achievement Award in 1994.

Hill was able to publish widely as well. In addition to the textbooks and reports already noted, she has contributed chapters in the yearbooks of the NCTM, the National Society for the Study of Education, and the National Education Association. She served as associate editor of *The American Mathematical Monthly* from 1973–1977, and was a member of the editorial panel for the 1973 NCTM Yearbook, *The Slow Learner in Mathematics*.

Shirley Hill was named Curators' Professor, the highest and most prestigious academic rank in the University of Missouri System, at UMKC in 1987, reaching a high level on the staircase. She is currently retired and living in the Kansas City area. For more about her career, see [3] and [5].

7.9 Deborah Tepper Haimo

Deborah Tepper (Figure 7.7) was born in Odessa, Ukraine, and also lived in Israel (at that time, Palestine) before her family moved to the U.S. when she was 11. She was not interested in a high school teaching career because she knew [8] that in Boston, where she lived during her teenage years, married women were not allowed to teach in the public schools. This was around 1940. She had fallen in love with mathematics early, and did her undergraduate work at Radcliffe, where she met Franklin Haimo while she was an undergraduate and he a graduate student in a Harvard class taught by Saunders Mac Lane. They were married (each combining the other's surname with their own) and moved to St. Louis when Franklin finished his doctorate in 1947 [15], and began a large family, something they both wanted, and for which Deborah willingly delayed her mathematical research career. Together, they adapted the myth to create their own life course for couples who are both mathematicians. Five children and two advisors later, she finished her doctorate at Harvard in 1964, while mainly living in St. Louis. Her advisor at first was Hassler Whitney, who had recognized her abilities early in her time at Radcliffe and who was also Franklin's doctoral advisor. But when Whitney moved to the Institute for Advanced Study, she had to change, and finished, after another delay, working with David Widder. Her dissertation was *Integral Equations Associated with Hankel Transforms*.

In St. Louis, Deborah taught at both Washington University and at Southern Illinois University, Edwardsville, while the children were young (taking a semester off for each birth) before being hired at the University of Missouri-St. Louis in 1968. This was just five years after UMSL was established, and Deborah was instrumental in building up the mathematics program there, serving two terms as chair. The Tepper Haimos did quite a good job of supporting each other and sharing the duties of everyday life while building their mathematics careers, and were also notable for instilling high degrees of self-reliance, mutual support, and responsibility in

Fig. 7.7 Deborah Tepper Haimo ©Mathematical Association of America, 2017. All rights reserved

their children. They both had respectable research records, she in analysis and he in algebra, with Deborah publishing more than Franklin, despite her delayed start. More specifically, she published over 40 papers in many highly respected journals, mostly in harmonic analysis, especially relating to the heat equation, and integral transforms and series. Franklin advised seven doctoral students at Washington University, but Deborah did not teach at schools with doctoral programs, although she was instrumental in getting one started at UMSL. One of their daughters, Varda, received a doctorate in mathematics from Harvard in 1984. As a couple, the Tepper Haimos achieved almost all of the benchmarks of the myth, except for the part about immersing themselves in mathematics to the exclusion of all else. That part was replaced by a mutual commitment to family and children at least equal to their commitment to mathematics. In fact, for them, these two commitments were very nicely merged together in their lives.

Deborah Tepper Haimo was quite active in the MAA at the national level, culminating with a term as MAA President in 1991–92. During her term as president, she led in the reorganization and streamlining of the MAA committee structure, though probably not to the degree she at first had hoped - she was heard to say she wanted to end her term as president with fewer committees than when she started! This was a noble goal, and it didn't happen, but the reorganization she promoted "made order out of chaos," [14], and has served the MAA well. Her most lasting accomplishment was the establishment of what we now know as the Deborah and Franklin Tepper Haimo Awards for Distinguished College or University Teaching of Mathematics. This award honors college or university teachers who have been recognized as extraordinarily successful and whose teaching has been shown to have had influence beyond their own institutions. She received the Gung and Hu Award for Distinguished Service in 1997. After retirement in 1992, Haimo moved to La Jolla, California, in part because, as she noted, “it was always warm,” and became active in the University of California, San Diego mathematics department, where she held an honorary appointment. She died in 2007. See [8, 14] and [15] for more details about her life and career.

7.10 T. Christine Stevens

Christine Stevens (Figure 7.8) was born in Maryland and, due to the nature of her father’s engineering career, had lived in at least four states by the time she graduated from high school in New Jersey. She did her undergraduate work at Smith College where her major shifted from chemistry to applied mathematics to pure mathematics. With acceptances from Princeton, Cornell, and Harvard for graduate study, she picked Harvard. Once there, she found that several of the other graduate students had already taken graduate mathematics courses as undergraduates, putting her on what she termed the “remedial track” [25], despite a good background from Smith, which included undergraduate research and a senior project. Harvard is a popular place for those following the myth. Stevens successfully overcame her relative lesser background, and received her doctorate from Harvard in 1978 with advisor Andrew Gleason. Her dissertation was *Weakened Topologies for Lie Groups*.

As related in [25], Stevens’ transition from science to pure mathematics was due in part to her realization that a lot of applied science and applied mathematics had to do with weaponry and warfare, and she was not comfortable with the idea of having a career with that component. Active in the antiwar movement, in 1972 she recruited Thomas Moisan, a graduate student in English at Harvard, to work on the McGovern campaign. They were married two years later. So the same reason that drew her towards pure mathematics also was instrumental in bringing her together with her future husband. Stevens and Moisan created a combined life course as a couple in which each was able to grow and develop professionally in their respective fields.

Stevens taught at Lowell State College (now University of Massachusetts Lowell) while finishing her degree, and then got a position at Mount Holyoke College in Massachusetts. Moisan got a position at Middlebury College in Vermont after finishing at Harvard, so the couple found themselves maintaining apartments in two states. The New England states are small, but not that small. Deciding to seek positions at one institution, in 1981 they accepted offers from Arkansas State University in Jonesboro, Arkansas. During the next eight years, however, only half were spent in Jonesboro. ASU had agreed to a sabbatical (unpaid) after their first year, and they took it in Cambridge, England. Stevens worked on topological groups and Lie groups, while Moisan, who was a Shakespearean scholar, also had a productive year. Then, supported by the ASU president, who was a former

Fig. 7.8 T. Christine Stevens circa 2010 (photo provided courtesy of Christine Stevens)

U.S. congressman, Stevens became the 1984–85 AMS/MAA/SIAM congressional science fellow. After a couple of years back, she next was a program officer in teacher enhancement at NSF for two years. During their years in Washington, DC, Moisan did not stay in Arkansas; he did research at the Folger Shakespeare Library the first time and then taught at Mary Washington College while Stevens was at NSF. So it is unclear whether they resigned from Arkansas State in 1987 or in 1989. In any case, in 1989 Moisan was offered the chair of the English Department at St. Louis University, and Stevens was hired in the SLU mathematics department. Later, Stevens became chair of the SLU Mathematics Department while Moisan was still chair of English. In [25], Stevens remarks that some of the administrators were uneasy about those two departments being "in bed with" each other. Even with the uneasiness, this was evidence of progress made since the not-so-distant past when Stevens would not even have been hired in the first place.

In 1992, looking for a way to help new PhDs in mathematics get a good start in academia, Stevens and Jim Leitzel founded Project NExT (New Experiences in Teaching) and, after Leitzel's death in 1998, Stevens was sole director of the project until 2009. For the first eighteen years Project NExT was sponsored by the Exxon Education Foundation and its successor, the ExxonMobil Foundation. Still operating, Project NExT had over 1000 participants during Stevens' time as director and is widely recognized as one of the most successful and valuable programs in the history of the MAA. To learn more about Project NExT and Stevens' role in it, see [18] and [25].

In addition to her many contributions to mathematics education, Stevens has maintained an ongoing research program in topology; her latest paper listed on MathSciNet is from 2015. At SLU, she advised two doctoral students, making her the only woman discussed in this paper to have mathematical descendants (and thus checking that particular box of the myth). She has been not only active, but also a leader in mathematics professional organizations. In addition to her time at NSF, she chaired the MAA Science Policy Committee, served on the Task Force for Minorities in Mathematics, and was appointed to the Committee on Minority Participation in Mathematics. In 2004 she received the MAA Gung and Hu Award for Distinguished Service, and in 2015 was presented with the Association for Women in Mathematics Louise Hay Award for her outstanding achievements in mathematics education, broadly defined. In 2010 Smith College named her a recipient of the Smith College Medal, "established in 1962 to recognize women who exemplify in their lives and work 'the true purpose' of a liberal education" [26]. In 2015 Stevens was elected as a Fellow of the AMS. Currently, she is Associate Executive Director of the American Mathematical Society and Head of the Meetings and Professional Services Division.

7.11 Conclusion

While working on this project, my biggest regret is that although I have met in person two of the women (Haimo and Stevens), I could have met all the others except Wyant, who died before I was born, if I had known, then what I know now and sought them out. I am envious of Murray's experiences personally interviewing the women for her book [20]. That's another problem with the myth - it encourages, practically demands, a narrow focus. If you eat, sleep, and breathe mathematics, you probably will miss knowing some people who could have enriched your life. Go ahead and prove theorems and write books, but get out and meet others along the way, too.

According to Euclid, "There is no royal road to geometry." He was right. Even realizing the myth requires hard work and dedication. Each of these women followed or created her own road to a mathematics career, and each can serve as an example of success in mathematics for any aspiring mathematician, man or woman.

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Chapter 8
Celebrating the Contributions of Three Women to Mathematics Teaching and Learning

Jacqueline M. Dewar

Abstract This chapter celebrates the lives and accomplishments of three women mathematics educators whom the author has had the privilege to know. The three women are Ruth Afflack (California State University Long Beach), Natalie Ambrose (Immaculate Heart High School), and Teri Perl (The Learning Company), two of whom were highly engaged in the Association for Women in Mathematics during its early years. All three were mathematics teachers at some point in their lives, but all three were also agents of change. This chapter summarizes many of their professional accomplishments and the impacts of their outreach and activism during the latter half of the 20th century and encourages readers to reflect on the contributions of the mathematics educators they have known.

Keywords Mathematics educator • Agent of change • Mathematics teaching • Expanding Your Horizons Career Day • Math/Science Interchange • Math/Science Network

8.1 Introduction

When a co-organizer of the Contributed Paper Session "The Contributions of Women to Mathematics: 100 Years and Counting" at MathFest 2015, sponsored by the Association for Women in Mathematics (AWM), encouraged me to submit an abstract to the session, I decided to propose a talk honoring three women mathematics educators whom I have known personally. That talk, and this resulting chapter, celebrate the lives and accomplishments of three women in California who made contributions to mathematics education during the second half of the 20th century: Ruth Afflack (1932–2008), Natalie Ambrose, IHM (1930–2016), and Teri Perl (1926–). All three were mathematics teachers at some point in their lives,

J.M. Dewar (✉)
Loyola Marymount University, Los Angeles, CA, USA
e-mail: jdewar@lmu.edu

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but all three did much, much more. Each authored books or educational materials, joined with others to found one or more organizations, and had a significant impact on many, including me. This chapter will describe their contributions as teachers, authors, and agents of change.[1]

Knowing the context for the work of these three women in terms of time and place is necessary to understand fully its significance. I will begin by discussing some aspects of mathematics teaching in the middle of the 20th century. According to Dale Seymour, "even during the 1960s [in the United States and Canada] most mathematics teachers followed the text faithfully and exclusively" [43, p. 989]. In California, K–12 education mandates and reforms abounded. "Between 1958 and 1975, fifty-two education reform initiatives were penned in Sacramento [the state capital]. In the mid-1980s, educators were directed to 'teach for understanding,' to use small groups and hands-on 'manipulatives,' and to move away from traditional... tests" [48, p. x]. As we shall see, the three women in this chapter were way ahead of the curve. Well before the 1980s, they designed and taught with hands-on activities using manipulatives and had their K–12 and college students exploring and solving problems and puzzles that were not in the textbook. In addition, one of the three was at the forefront of developing educational software for classroom and personal use.

As early as the mid-1970s, these women were involved in, even initiating, programs and organizations to encourage girls and women to continue their study of mathematics. Part of the impetus for these efforts came from sociologist Lucy Sells' 1973 study of entering freshman at the University of California, Berkeley, which showed that 57 percent of the boys took four years of high school mathematics compared to only 8 percent of the girls. Not taking four years of high school mathematics excluded students from college courses in calculus, chemistry, and physics that were "required for majoring in every field at Berkeley except the 'traditionally female' (and hence lower paying) fields of humanities, social science, education and social welfare" [42, p. 2]. Because of this study, mathematics came to be seen as a "critical filter," severely limiting career choices for women and for minorities who did not take four years of high school mathematics. Also in the mid-1970s, the concept of "math anxiety"—a phrase popularized by Sheila Tobias [46, 47]— and its relationship to math avoidance gained broader understanding and acceptance; as a result, mechanisms to address these began to emerge. One of the women in this chapter developed a course and a weekend workshop to help students overcome their fear of mathematics.

[1] Because of my personal connection and friendship with each of these women, I found it difficult to observe the formal convention for academic writing of referring to individuals by their last names. I hope the reader will not feel that my use of their first names in what follows diminishes the power or impact of their stories.

Fig. 8.1 Ruth Afflack (photo acknowledgement: Department of Mathematics and Statistics, California State University Long Beach)

8.2 Ruth Afflack

8.2.1 Meeting Ruth

The early years of the AWM, in the 1970s, were a time of activism and of speaking out politically, forcefully, and directly, reporting what was observed and experienced. According to Lenore Blum, the third president of AWM, "It was also a time of lassoing people in. In addition to national meetings of the AWM, members were organizing and meeting regionally ..." [7, p. 746].

I met Ruth Afflack (Fig. 8.1) at one of those meetings, a potluck attended by about 12 women that she helped to organize in Los Angeles. As a direct result of this meeting, we planned presentations at local mathematics conferences for K–12 mathematics teachers and collegiate mathematics faculty about the problem of young women avoiding mathematics.[2] We wanted to do something more to spread the message that women could and did do mathematics, so we decided to reach out to younger women, girls in junior and senior high, to encourage them to study mathematics and science. This resulted in a broader message and enabled us to recruit local women scientists as well as mathematicians to participate. Ruth shared information with the group about San Francisco Bay area programs focused on encouraging women and girls to study mathematics and science, including the Expanding Your Horizons (EYH) Career Days. The EYH Career Days are one-day programs offered for middle school and high school girls to inform them about careers in mathematics- and science-related fields. Students have fun in hands-on

[2] e.g., the Fall 1976 Convention of the California Mathematics Council and the Spring 1977 Southern Section Meeting of the Mathematical Association of America

workshops led by women with careers in science, technology, engineering, and mathematics (STEM), learn about STEM-related careers, and interact with positive role models. The programs also include workshops for parents and educators about encouraging mathematics and science as a career option for girls. The decision to plan an EYH Career Day in Los Angeles led to ongoing collaborations with Ruth and set the stage for my meeting Natalie Ambrose, IHM, the focus of Sect. 8.3 of this chapter.

8.2.2 Ruth as Teacher, Colleague, and Author

Ruth was born in Pittsburgh, PA in 1932 and received her bachelor's and master's degrees from the University of California, Santa Barbara. She was a faculty member in the mathematics department at California State University, Long Beach (CSULB) from 1966 to 1992. [3] Upon retirement, Ruth was honored with emerita professor status; by then, the significance of her contributions to the department in the area of mathematics education was recognized. In an email announcing Ruth's death to the department, Robert Mena, department chair at that time, observed that she was "one of the leaders in Math Education in the department in the early years" and cited as one of her many contributions that she "developed and taught for years a successful course for students with math anxiety (of which there are many)" [28].

I remember conversations with Ruth about her efforts to get a designated position for mathematics education that resulted in the 1985 hiring of Lindsay Tartre, the first CSULB Mathematics and Statistics Department faculty member with a PhD in Mathematics Education. Tartre acknowledged that she owed much to Ruth: "She fought many battles that smoothed the way for my position to exist. She was a force to be reckoned with" [45]. Still, Tartre felt that, in the early years of Ruth's career, not having a doctorate made it difficult for Ruth to get respect from the other mathematicians in the department, particularly since she was a woman. But Ruth did succeed in building a strong base for work in mathematics education at CSULB. According to Tartre, by 2015 the department had six faculty members with degrees in mathematics education.

Ruth was also known for designing and implementing educational programs to increase the participation of females in mathematics [10]. Working to increase her students' confidence in their ability to do mathematics was a hallmark of her teaching, whether it was future teachers, "re-entry" women (a term used in the 1980s to describe mature women returning to college after a long hiatus from school), or those in weekend workshops on overcoming math anxiety that she offered through CSULB's continuing education division [1]. Ruth invited me to visit her "Mathophobia" workshop and then mentored me in developing my own

[3] In the 1960s, having a doctorate in mathematics was rarely required for a tenure track position at a non-PhD granting institution like CSULB.

Overcoming Math Anxiety workshop, which I offered through continuing education at Loyola Marymount University (LMU) in the late 1970s. We even co-authored a paper about math anxiety, which we presented at the Seventh Annual Conference on Feminist Psychology in Los Angeles in 1980 [3].

In [1], Ruth described how her participation in Project SEED (Special Elementary Education for the Disadvantaged) prompted her to change her methods of teaching. This program placed mathematicians in elementary classrooms for short periods daily to motivate students by using the discovery method of teaching mathematics. She realized that the inner-city school children were excited by this inquiry approach that used games and activities, while the traditional method of teaching the CSULB mathematics for elementary teaching course was not reaching prospective teachers. She began incorporating games and activities to engage her college students and demonstrate that mathematics can be fun and challenging. She emphasized pattern recognition (and connected it to the concept of function), encouraged guessing (to get students to take a first step), and had her students verbalize their reasoning. Problem-solving strategies were discussed throughout the course and not covered just as a special topic (like word problems are often treated in algebra). Students overcame their fears and gained mathematical confidence as they worked in the supportive environment provided by Ruth. Ruth included many of these activities for engaging people in mathematics, and described how to promote a positive classroom environment, in her book *Beyond Equals: To Encourage the Participation of Women in Mathematics*, published in 1982. The book was intended for instructors of adult women who wanted to "encourage [the] women to participate in mathematics and to provide them with the skills necessary to do so" [2, p. 1]. Ruth insisted that "[emphasizing] problem-solving, concrete representations, logical reasoning, and spatial experiences" [2, p. 1] were essential to effective instruction in any type of overcoming math anxiety course.

I can readily point to a long-term impact that Ruth's work has had on more traditional mathematics students. Many of her ideas and problem solving exercises from *Beyond Equals* and from her Mathophobia class have found their way into the problem-solving portion of a course for beginning mathematics majors that has been taught for 25 years at LMU [17].

Many have acknowledged Ruth's work and assistance in print. The following four examples hint at the breadth of her efforts and generosity: she is noted for suggesting many improvements at the manuscript stage of an abstract algebra text [29], *Ms. Magazine* cited her work in helping women overcome math anxiety [46], a book about the complexities of being a woman in mathematics discussed Ruth's work in organizing regional meetings in the early years of AWM [12], and a book on study skills acknowledged her for allowing use of her ideas on helping students learn mathematics [32].

8.2.3 Ruth as an Agent of Change

Ruth joined with others to found not one but two non-profit organizations: Math/Science Interchange (M/SI) and the Peter Carr Peace Center. M/SI, formed in

1978 by Ruth and three other college mathematics professors (Susan Montgomery at the University of Southern California, Dena Patterson at Santa Monica College, and the author), was an outgrowth of regional meetings and activities of AWM in the Los Angeles area. M/SI's goals included increasing the awareness of young women regarding mathematics- and science-related careers, encouraging participation in high school mathematics and science courses, and providing role models for young women interested in mathematics and science. M/SI's name and activities followed the model of the Math/Science Network, founded four years earlier in the San Francisco Bay area (see Sect. 8.4.3). The word "Interchange" was chosen as part of the name both for its obvious meaning and as an inside reference to freeway interchanges, befitting M/SI's location in Los Angeles. Today its Board of Directors consists of "academic and industry professionals committed to bringing math and science opportunities to young women in the Los Angeles area, particularly those residing in the inner city" [27]. With no paid staff, M/SI has organized annual EYH Career Days for girls in grades five through eight since 1979 [20].

In addition to advocating for women and empowering them through mathematics, Ruth was deeply committed to social justice more broadly. Ruth was among the network of faculty, students, staff, and community members who shared values of peace, social justice, and environmental sanity and who founded the Peter Carr Peace Center, now called the Center for Peace and Social Justice, at CSULB in 1981 [10]. The Center's activities have included: establishing the Peace Studies Program, resisting ROTC and the militarization of campus, organizing the campus opposition to the first Gulf War, and opposing the commercial development of a piece of CSULB land that was once the site of a Native American village [14].

After her retirement, Ruth moved to southern Washington State where she bought ten acres of land. She died in 2008, but her generosity and commitment to the environment live on through her bequest of that land to the Puget Consumers Co-op (PCC) Farmland Trust. PCC is the largest consumer-owned food cooperative in the United States. The Co-op founded the non-profit trust to secure and preserve threatened farmland in the Northwest, so that future generations of local farmers can continue to farm it. Ruth's bequest led the PCC to establish the Ruth Afflack Stewardship Fund in her honor, to continue the work of the organization in preserving farmland [33].

8.3 Natalie Ambrose, IHM

8.3.1 Meeting Natalie

I first met Natalie Ambrose (Fig. 8.2) through planning an EYH Career Day conference in the mid-1980s. We needed another leader for an adult workshop, and someone suggested Natalie. She became a regular, leading workshops for adults and for students, and for many years she pitched in to help with conference planning. Her 1988 EYH workshop for adults titled "Paper Folding and Picture Taking"

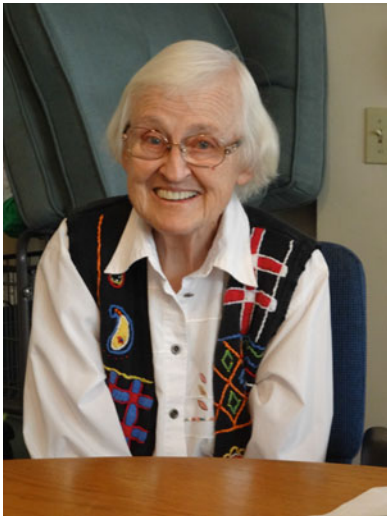

Fig. 8.2 Natalie Ambrose, IHM (photo acknowledgement: Jacqueline Dewar)

combined two of her passions, hands-on mathematics and photography. A student workshop titled "Can You See It in Your Head?" made use of art and graphics to explore symmetry and optical illusions. She loved making connections between mathematics and art.

Later on, I learned from personal experience how kind-hearted Natalie could be. At a stressful time in my life, she invited my 13-year-old daughter and me to spend the weekend at her house in Green Valley, a small unincorporated community about 60 miles from Los Angeles. That weekend provided us with a much appreciated respite and is one small example of Natalie's generosity to others.

8.3.2 *Natalie as Teacher, Colleague, and Author*

Natalie was born in New York City in 1930 and attended Hunter College, where she earned a bachelor's degree and a teaching credential. She taught at Hunter High School right after graduation and then moved to California because she had relatives there. She taught mathematics at several California high schools: Paraclete High School in Lancaster, Mission High School in San Luis Obispo, and Immaculate Heart High School in Los Angeles, where she also served for many years as mathematics department chair. She did graduate studies in the Confluent Education program at University of California, Santa Barbara. According to [44, p. 85], confluent education "is grounded in a humanistic paradigm that emphasizes subjectivity, process, and personal development as opposed to models of learning that stress objectivity, performance, and mastery of subject matter." As a member of the program, Natalie researched the affective and cognitive aspects of learning and completed the degree requirements, but not the dissertation, for a doctoral degree.

To learn more about Natalie as a teacher, I drafted an email that was distributed in June 2015 by the alumnae office of Immaculate Heart High School to those who graduated during the years that Natalie taught there. It asked anyone who had taken a class with Natalie and later went on to be a mathematics teacher to respond about her influence on their teaching. Many replies came back, and not just from those who had gone into teaching. I also heard from a nurse, an investment banker, two artists, a hospice registered nurse case manager, and many others. This reply from Nancy Perry was typical of the sentiments they expressed: "I loved Sr. Natalie, she was an inspiration, an encouragement, a force of nature, JOY, and fun when it came to math.... I did not go onto become a math teacher, though I did homeschool our son through the 8th grade ... AND I cannot watch basketball without thinking about geometry, Sr. Natalie, and smiling" [41].

While Natalie did not publish books or journal articles, she did write educational materials for student use and for sharing at conferences, as well as some personal reflections on teaching. She presented many conference workshops, talks, and in-service training sessions. Whether she was teaching a class, an in-service program, or a conference workshop, everything was "hands-on" and "minds-on." In fact, just about all the photos available of her through the Immaculate Heart High School archives show evidence of her using hands-on materials to engage minds.

Natalie attributed her approach to teaching mathematics to the education that she received at Hunter College in the 1940s [personal interview, June 7, 2015]. She shared her ideas and materials widely [15, 31]. Her reflections from 1973 on the "creative process" and ways to help students experience the infinite, the infinitesimal, and the interrelation between the two seem far ahead of their time in their content and pedagogical approaches [4]. In her introduction, she made reference to Maslow and Piaget, commenting, "I think these activities give opportunity for an 'ah-ha' experience; when a student begins to play with these ideas on her own, I think there can be points of transcendence as she grasps the concept of time and space. I think the mathematical tools help her jump the gap from concrete to abstract" [4, p. 2]. Natalie then presented 20 activities and exercises to enable a student to develop a sense of the following concepts: non-terminating process; continuing reduction in size; paradox (coming closer and closer but not reaching); number as a symbol for an abstract idea; and coming to a new idea through pattern.

Natalie also engaged in a number of non-mathematical activities that involved students or teachers. She was a physical education teacher when she first came to California, and she earned money as a referee for girls basketball; she even had a national rating as a referee. She worked as a sales representative for Dale Seymour Publications (now part of Pearson Learning group) at local and regional mathematics conferences focused on K–12 teaching for two reasons: she thought Dale Seymour's materials were, as she would say, "mahvelous" and they were inexpensive, which she knew was important for teachers! Marvelous is a word Natalie was known for saying in that very particular way, both in and outside of the classroom.

Mary Fay-Zenk, a graduate of Immaculate Heart High School who went on to become a high school mathematics teacher, gave the eulogy at Natalie's funeral. In her moving tribute, she recounted her own memories of Natalie and those of her three sisters who had also had known Natalie, either as a teacher or a dance team coach, at Immaculate Heart High School. Fay-Zenk quoted her sister Katy, now a mathematics instructor at California State University, Chico, as follows: "Natalie made it make sense! She was so far ahead of her time in that respect. She could have written the new Common Core standards in which a primary goal is that students make sense of problems and persevere in solving them" [23]. Fay-Zenk also recounted how a good friend of hers, a mentor teacher and teacher leader in Cupertino, had excitedly shared an Origami Star lesson. The opening paragraph of the lesson included this acknowledgement: "Natalie Ambrose demonstrated how to make the Octagon Stars at the California Mathematics Council Conference in Long Beach in November, 1987" [23, 31]. Fay-Zenk described the poignant moment when she told her friend, "... that's Natalie, that's my high school teacher whom I'm always telling you about!" [23].

8.3.3 Natalie as an Agent of Change

In 1953, Natalie joined the Sisters of the Immaculate Heart of Mary, a traditional Roman Catholic religious order of nuns with a history dating back to 1848. In response to the second Vatican Council's call for renewal in the mid-1960s, this religious group began to modernize their dress, relax their strict rules about what to do at what time (the rules literally governed when to pray as a group, when to turn lights out at night, and so on), and seek out more active ministries. The sisters soon encountered difficulties with church officials in Los Angeles and eventually the only "solution" open to them was to start a new and independent community, the Immaculate Heart Community [11, 13]. In 1970, Natalie joined with 400 of the Immaculate Heart sisters to found this new community. Today, the Immaculate Heart Community is made up of dedicated men and women with a mission to create community, to work as advocates for the marginalized, for social and economic justice and peace, and for the integrity of creation [26]. Natalie served as the vice president of the community from 1981 to 1987. The community currently runs the all-girls' Immaculate Heart High School and the Corita Art Center, both in Los Angeles, and a retreat center in Santa Barbara, California, and does other forms of outreach.

Natalie also helped frame public policy and advocated for the rights and welfare of the elderly. She served as a Commissioner and two-term Chair of the Los Angeles County Commission on Aging, a consultant to the Children's Planning Council in the San Fernando Valley and the Antelope Valley in California, and Director of Planning and Aging for the United Way in Antelope Valley. Reflecting on her involvement in so many civic, aging, and health organizations, Natalie wrote, "The issues of aging, technology, and culture shifts make this an interesting time to be involved with these projects. These factors also affect our Community" [9].

Fig. 8.3 Teri Perl (photo acknowledgement: Teri Perl)

8.4 Teri Perl

8.4.1 Meeting Teri

My original connection to Teri Perl (Fig. 8.3) took place long before I first corresponded with her in 2011 and met her in person in 2012. It was her 1978 book, *Math Equals: Biographies of Women Mathematicians + Related Activities* [35], which had a significant effect on me and the trajectory of my career. I was taking a graduate course in ring and field theory in 1969 when I first heard that a woman had made significant contributions to mathematics—that woman was Emmy Noether. Nearly a decade later, by reading *Math Equals* as an assistant professor at LMU, I discovered the stories of nine women, including Noether, who had achieved some degree of recognition for their contributions to mathematics. Along with the nine biographies, Teri's book contained mathematical activities related to the work each woman had done and a discussion of the situation for women in mathematics in the United States at that time. Her book inspired me to develop a general education mathematics course on women and mathematics. It also gave me a model for combining mathematical biographies and activities with discussions of gender issues (for more information on this course, see [16, 18, 19]). Since *Math Equals* was written for high school students, the mathematical activities were at an appropriate level for the typical student in a general education mathematics course. The course, initially titled "Mathematics: Contributions by Women," was first offered in 1979. I continued to teach a version of it whenever the department's schedule allowed me to do so.

From a small notice in the May–June 2011 issue of the *AWM Newsletter*, I learned that *Math Equals* was out of print and that Teri was offering the remaining copies at a very reduced rate. I thought, "What would I do without that book as a foundation for the course the next time I taught it?" I decided to buy a classroom set of 20 to have on hand for future offerings of the course, but then learned that all copies were already gone. So instead I emailed the author to ask permission to make copies for my students. Making that request was my first contact with Teri. Of course, she graciously and generously granted permission to do so. It turned out that Teri has some relatives in Los Angeles, so we were able to meet in person when she came to visit them in 2012. Since then, we have had many conversations via Skype, telephone, email, and twice in person about teaching, about women and mathematics, about writing an updated version of the book aimed at a more mathematically sophisticated audience, and about family, friends, and life in general.

8.4.2 Teri as Teacher, Colleague, and Author

Teri was born in New York City in 1926 and earned a bachelor's degree in economics from Brooklyn College. While earning a secondary mathematics teaching credential at San Jose State University in San Jose, CA, she did her student teaching at Mountain View High School. Because of her husband's upcoming sabbatical in England, she opted to do substitute teaching rather than seek a full-time teaching position. Her experience as a substitute teacher led her to realize the need for good lesson plan materials for substitute teachers. Serendipitously, because both of their husbands were physicists, Teri met Miriam Freedman, a language arts substitute teacher on the East Coast who had made a similar observation. Despite the fact that they were on opposite sides of the country and well before any Internet or email communication was available, the two women struck up a clever collaboration to write *A Sourcebook for Substitutes and Other Teachers*, published in 1974 [24]. They prepared and class-tested games, puzzles, and activities in a variety of subjects: Miriam in English, foreign languages, and social science and Teri in mathematics and science. They included practical suggestions ranging from "learn school procedure" and "start class immediately" to "be enthusiastic" and "keep the activity moving by giving hints or answers" in the book. Complete lesson plans describing the objectives, materials needed, how to group students, procedures, and variations were provided for each activity. Quite a variety of mathematical topics were touched upon, ranging from straight lines and coordinate systems to magic squares, the Fibonacci sequence, Euler circuits, and the Jordan curve theorem. As one user commented online in 2013, "I have been teaching for 19 years and STILL use this book! It was a Godsend when I was substitute teaching!!" [5].

Teri taught part-time at San Francisco State University while earning her doctorate in mathematics education at Stanford University, which she received in 1979. Her dissertation used a large longitudinal data set to explore what factors were important in explaining sex differences found in high school students who elected to take mathematics courses beyond the minimum required for graduation or entrance to college. A cluster of variables related to ability and achievement was the most significant factor. However, "sex differences in the means of the variables that comprise[d] this factor [were] not great enough to explain the large differences in electing patterns" [37, p. 71]. Teri's research identified "perception of usefulness" as the key factor in explaining the remaining variance [37].

Teri has published an eclectic set of books and articles (see, for example, [24, 30, 34–40]). In addition to *Math Equals* and *A Sourcebook for Substitutes*, there are two more books related to women and mathematics. *Notable Women in Mathematics*, co-edited with Charlene Morrow, contains profiles of 59 women mathematicians across the ages and from around the world [30]. *Women and Numbers: Lives of Women Mathematicians plus Discovery Activities*, includes the biographies of 12 women from the 19th and 20th centuries who pursued mathematics [38], as well as mathematical activities written for middle school students.

In a 2003 book on the history of school mathematics, Teri co-authored a lengthy and informative chapter that examined "the response of the mathematics education community to the changing population in the United States since the Second World War" [6, p. 1085]. But the publication that Teri says she is most proud of is her article on the *Ladies' Diary* that appeared in *Historia Mathematica* [36]. The *Ladies' Diary* was an 18th century English magazine primarily devoted to mathematical problems and puzzles. Teri explained her motivation for looking into this magazine as follows: "Researching the *Ladies' Diary* in the 1970s was important as a way to help overcome the then current attitude that math was hard for girls–implying that it was easy for boys. Learning about the existence of the *Ladies' Diary* was important then because it showed that, even so long ago, given the proper education and the opportunity, women were certainly capable of understanding and enjoying mathematics. So why were these sex differences in attitudes towards mathematics still persistent in the 1970s?" [40, p. 15].

8.4.3 Teri as an Agent of Change

Teri was part of an informal group of women mathematicians, scientists, and educators in the San Francisco Bay area who were concerned about low female enrollment in mathematics courses. In 1974, they founded Math/Science Network, an organization that changed its name to the Expanding Your Horizons (EYH) Network when it gained nonprofit status in 1982. Its mission is to inspire girls to recognize their potential and pursue opportunities in STEM [22]. Early on, its leaders designed a one-day program for middle school and high school girls consisting of hands-on workshops led by women with STEM careers to demonstrate there were enjoyable, well-paid careers in STEM fields for women.[4] At this writing, more than 80 EYH Career Days take place annually in the US, Europe, and Asia, serving up to 25,000 junior and senior high girls [21]. Teri served as president of the EYH Network from 1999 to 2007. The EYH Network also offers help to

[4]These are the EYH Career Days first mentioned in Sect. 8.2.1

anyone wanting to start a conference at a new location. At the 30th anniversary celebration of the EYH Network, Lenore Blum [8] acknowledged Teri's many contributions, ranging from being a founding member, to serving as president, to being the inspiration behind the celebration.

In 1980 Teri was a co-founder of The Learning Company, an educational software company. The Learning Company began "when there were no big-name educational software companies—just beginning programmers and educators looking to make a difference" [39]. It went on to produce cutting-edge educational software for young children, including Gertrude's Secrets, Gertrude's Puzzles, Reader Rabbit, Math Rabbit, and Rocky's Boots. Teri was the content designer for Math Rabbit. When teacher editions were developed for school use, Teri wrote several of the teachers' guides to accompany the software programs and supervised the production of the school editions. Anyone reading this who had young children in the 1980s may have purchased some of these programs for them, as I did. The company continues as part of Houghton-Mifflin-Harcourt.

GirlSource honored Teri with its WAVE (Women of Achievement, Vision and Excellence) award in 2005 [25]. GirlSource is a non-profit organization located in San Francisco that provides programs for young women ages 14 to 18 from low-income families to equip them with leadership and job skills they need to succeed. The citation for the award praised Teri's research into what discouraged girls from taking elective mathematics courses in high school [37]; her work in encouraging young women's participation in mathematics and science, especially her founding of Math/Science Network and The Learning Company; and her books. It is also worth noting that Teri's book *Math Equals* was cited in the American Library Association's *Choice* magazine for outstanding contributions to mathematics.

8.5 Closing Thoughts

Readers will surely note common themes and connections among the lives and work of these three women mathematics educators. Ruth, Natalie, and Teri each began her life on the East Coast and made her way to California, where she undertook graduate studies in mathematics, education, and mathematics education, respectively. As teachers, they each developed new, inventive ways to encourage student learning through the use of games, puzzles, and hands-on experiences. All were devoted to encouraging girls and women to participate in mathematics. They were extremely generous, sharing their time, ideas, and materials with others. In gathering information for this chapter, I received two testimonies, one for Ruth and the other for Natalie, describing them as a force to be reckoned with and a force of nature, respectively. I can confirm that this sentiment is also quite apt for Teri.

As their accomplishments attest, Ruth, Natalie, and Teri were activists for significant causes both in and outside of mathematics. To the best of my knowledge, none of these women published any traditional mathematical research. But they certainly did make a difference through their various contributions to mathematics teaching and learning. All were pioneers, leaders, and mentors to many, including me. It is my hope that readers of this chapter will not only join me in celebrating them, but also be prompted to reflect on the contributions of mathematics educators whom they have been privileged to know.

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Chapter 9
The Krieger-Nelson Prize Lectureship

Laura E. Turner

Abstract The Krieger-Nelson Prize Lectureship honours outstanding research by women members of the Canadian mathematical community. First awarded in 1995, it is named after Cecilia Krieger (1894–1974), the first woman to earn a Ph.D. in mathematics from a Canadian University, and Evelyn Nelson (1943–1987), a prolific researcher in universal algebra. In this chapter, we explore the origins and early history of this prize. Beginning with the social conditions which prompted the establishment of the Committee on Women in Mathematics of the Canadian Mathematical Society (CMS), we then turn to the first projects of this body and the decision of the CMS to establish a lectureship for women in mathematics. Finally, we consider the contributions of those reflected in its eventual name.

Keywords Cecilia Krieger • Evelyn Nelson • Krieger-Nelson Prize Lectureship • Canadian Mathematical Society • Women in mathematics

9.1 Introduction

From its inception, the Krieger-Nelson Prize Lectureship has honoured outstanding research by women members of the Canadian mathematical community. Established in 1995 by conscientious members of the Canadian Mathematical Society (CMS) paying increasing attention to the disparate opportunities and inequity faced by women mathematicians in Canada relative to their male counterparts, this prize emerged as an idea whose time had ultimately come.

In this chapter, we trace the origins and early history of this prestigious award through the lenses of the official newsletters of the CMS and recent personal communications from founding members of the prize itself. In doing so, we devote special attention to four matters: the social climate of the late 1980s and early 1990s and contemporaneous discussions within the CMS of the status of women members of the Canadian mathematical community; the creation of the CMS's

L.E. Turner (✉)
Monmouth University, West Long Branch, NJ, USA
e-mail: lturner@monmouth.edu

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Committee on Women in Mathematics (CWM)[1] and related initiatives promoting the equitable treatment and participation of women and girls within mathematics; the establishment of what ultimately became the Krieger-Nelson Prize Lectureship of the CMS; and the significance of the contributions and trajectories of Krieger and Nelson themselves in the meaning attributed to their namesake.

As we will see, both struggle and remarkable achievement were hallmarks of the legacies of Krieger and Nelson, and though the award pays tribute to the latter it also serves to remind us of the former. What is more, the juxtaposition of these two themes on a broader scale shaped the discourse and cast into motion the actions that realized the prize itself.

9.2 The Impetus for Change: Women in Mathematics, and the State of the Profession in Canada

The late 1980s and early 1990s saw the expression within the Canadian mathematical community of the broader feminist movement taking shape and a growing concern about the status of women at virtually all levels of the mathematical profession. In particular, discussions of affirmative action and the infrastructural and cultural hurdles faced by women mathematicians were becoming a regular feature of the semi-annual meetings of the CMS and its committees.

The Krieger-Nelson Prize Lectureship was created on the heels of, and in light of, many of these concerns. A closer consideration of some of the good, bad, and ugly features of the Canadian mathematical landscape of this period with respect to the status of women therefore provides important insight into the real and perceived significance of the lectureship at the time it was established, and the reasons for its very existence.

9.2.1 The Good, the Bad, and the Ugly

Several positive developments vis-à-vis the status of women in mathematics and science in Canada are noteworthy in the context of the present paper. By the 1990s, for example, a handful of systems had been put into place to encourage women within the sciences in Canada. Although it is difficult to measure their direct impact on mathematics, their existence is nonetheless demonstrative of a newfound push for increased participation by females quite broadly.

[1] Now the Committee *for* Women in Mathematics.

At the undergraduate level, the federal government's $80 million dollar [9] *Canada (Student) Scholarship Program* (CSP), which ran from 1988 to 1994, provided renewable funding for incoming students in the sciences, at least half of whom were to be female [52]. The latter point was emphasized "especially in the programs such as engineering or applied sciences where women's representation is the lowest" [9], though there was some concern on the part of the Education Committee of the CMS that mathematics be adequately represented [52].[2] Concordia and York Universities had also developed first year and summer research awards for female students [26].

As for faculty hirings, some universities had implemented affirmative action policies [26]. Above and beyond this, between 1990 and 1995 the Natural Sciences and Engineering Research Council of Canada (NSERC) offered roughly twenty *Women's Faculty Awards*, intended to help increase the number of women in faculty positions within science and engineering through university appointments which were frequently tenure-track [50].

Such a substantial program as the latter underscores the increasing attention paid during this period to women mathematicians and students, and the increasingly common remarks and queries about their scanty presence within all manner of professional and academic settings.[3] As noted by CMS contributor Kailash Anand in her three-part biographical series on women Ph.D.s of the Canadian mathematical community, "there is presently an acute lack of information concerning Canadian Women Mathematicians" [2]. Indeed, a 1993 report on the Government Policy Committee's second Annual CMS Professional Survey demonstrates incredulity in the passage:

> It is very surprising to me that we keep so little track of our own graduates. We don't know what happens to over 27% of our M.Sc. graduates, 9% of our male PhD graduates and 100% of our female PhD graduates!!! I find this last piece of data unbelievable, but that is what the survey said (I actually went back and looked over each one of the completed surveys again!) [32].[4]

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[2]This program, intended in part to "enhance Canada's international competitiveness by producing more scientific and technologically literate individuals", fell under the Mulroney government's "InnovAction" program [33]. It is difficult to track how many women recipients ultimately chose to study mathematics. One accessible cross-section, the 1994–1995 recipients at Memorial University of Newfoundland, yields comparatively fewer recipients in mathematics (3 males, 3 females) than other disciplines (engineering, for instance, had 11 males and 10 females). However, 25 female and 9 male "first year" students (who generally declare a major only at the *end* of their freshman year) also received awards. Overall, 65 of the 105 students to hold these awards at MUN were female [41]. At this point, MUN boasted 15,997 full- and part-time undergraduate students [42].

[3]During a 1989 Board of Directors Meeting, for instance, one member questioned why there were no female members on Canada's International Mathematical Olympiad team. It was responded that "no female student had attained the required level in the provincial or national competitions". Lily Yen had been the only female named to a Canadian team prior to that point. This occurred in 1984. Etsuko Amano would be the next, in 1990 [3].

[4]This reflects doctoral students who obtained their degrees between September 1991 and August 1992. Of them, 5 were female and 68 were male.

That such observations had been made and changes initiated reflects an unfortunate truth: by the early 1990s it was clear to many that the situation for women in mathematics was less favourable in Canada than they believed it could and should be. In [26], Asia Weiss described the situation in Canada circa 1990 as "rather grim". By her account, only 36% of bachelor's degrees, 27% of master's degrees, and 13% of doctoral degrees in mathematics were awarded to women. There was also a growing awareness that women and minorities were consistently, if unintentionally, passed over for jobs and professional honours, supported by the fact that while women held 15% of all university faculty positions, they made up only 5% of full-time faculty in mathematics departments (though close to 50% of part-time teachers).[5] There were no female editors of CMS journals in the early 1990s [18], and women were few and far between within the Board of Directors and Executive of the CMS.[6] Furthermore, it was understood that women mathematicians south of the border fared somewhat better [44, 46]. While Canada did have groups like the Society for Canadian Women in Science and Technology (SCWST) and Women in Science and Engineering (WISE), both founded in 1982, and the Committee to Encourage Women in Physics (CEWIP), founded in 1983 [35], in the United States the Association for Women in Mathematics, founded in 1971 "to serve and encourage women to study and have active careers in the mathematical sciences" was already well-established,[7] and percentages of women Ph.D.s and faculty members were demonstrably higher. According to the Second Report of the 1990 Annual AMS-MAA Survey, at that time, women (90 in total) comprised 22% of U.S. citizen new doctorates (among non-U.S. citizens, women represented 15% of new doctorates), 36% of the total graduate students, and 43% of undergraduates. Additionally, women numbered almost 20% of 1989–1990 new doctorates employed in the mathematical sciences at universities and colleges [40].

Numbers aside, mathematics in Canada saw a handful of far more troublesome issues during this period which thrust the chilly, even hostile, climate for some women scientists directly into the fore. The December 6, 1989, massacre of 14 female students at Montreal's École Polytechnique by a misogynistic male who claimed to be fighting feminism was described by the AWM as an "insane act of

[5] In this connection it was remarked that there seemed to have existed an invisible "quota system". As an example, the eight women non-plenary speakers at the 1994 ICM lectured in eight different sessions, almost "as if the selection panels although aware enough to consider women candidates, felt that they had fulfilled their duty as soon as the first one accepted". Similarly, a personal anecdote from the American mathematician and then-president of the AWM Cora Sadosky (1940–2010) recalls "a friendly colleague" discussing a potential junior hire in their field. When Sadosky mentioned one of the best junior researchers in the field (who happened to be female), he is said to have responded "But we already have a woman!" [45].

[6] The Board of Directors meeting minutes from May 29, 1991, for instance, lists 39 individuals under the headings "present", "invited", "regrets", or "absent". Of them, only three are women, none of whom were members of the CMS Executive.

[7] By one estimate, the AWM had over 3000 members (both men and women) by 1990 [5]. This may have been an overestimate; see http://www.awm-math.org/articles/199812/awm1990s/issues.html.

violence against women who were targeted because they had chosen to pursue a traditionally male-dominated career" [43], and led to a period of soul-searching for academics and professionals alike, who examined anti-female attitudes[8] amongst engineers and beyond. Patrick Quinn, a partner in a structural engineering firm from Toronto, "became a major voice within the [engineering] profession demanding that the incident couldn't be written off as the act of a madman" [6], and argued publicly that attitudes couldn't be changed unless women were actually hired [28]. To quote renowned Canadian metallurgist and physicist Ursula Franklin (1921–2016), "Yes, it was an act of a madman, but [. . .] what and who is hated, how it is expressed, is not unrelated to the world around us" [37]. To her, the stark realization that this could have happened at any Canadian institution represented "a quantum leap in reality recognition across the country", prompting "a discourse that looked for ways and means to rectify the unacceptable conditions in the study and work environments of women engineers" [30].

Unsurprisingly, the tragedy also resonated with Canadian mathematicians. At the 1989 CMS Board of Directors meeting, which took place in Montreal only two days after the shooting, members agreed officially "to join with the scientific community in expressing shock at the recent events at the École Polytechnique" [13]. The General Meeting of the society, held shortly thereafter, opened with the 48 attendees sharing a "solemn moment of silence" in memory of those who had lost their lives, and closed with a motion, carried unanimously, that the CMS President write to the Director of the École "expressing the meeting's sympathy". In it, the Society "in horror and anguish" addresses itself to the families, friends, fellow-students, teachers, and other associates of the women who lost their lives in the abhorrent attack. The letter closes with a "pledge that the meaning of our solemn moment of silence will not fade from our consciousness" [10].

The following year, new cries of outrage erupted when Gordon Freeman, a professor of chemistry at the University of Alberta, published his *Kinetics of nonhomogeneous processes in human society: Unethical behaviour and societal chaos* in the Canadian Journal of Physics (CJP) [31]. Freeman, who would publicly claim that the Montreal shooter "Marc Lepine's desperate act was an extreme example of the damage that feminists [referring to Lépine's mother] do to their children" [29], concluded in his paper that "the tendency to cheat correlates strongly with the absence of a full time mother in the home" and that "[a]bout half of the children of two-career families suffer serious psychological damage". Reactions to this piece, criticized as wholly unscientific and riddled with prejudices, spilled into the following years, and the journal's reputation was so severely damaged by this affair that the National Research Council (NRC), which published the journal itself, evidently considered shutting it down [51]. For their part, via an official letter drafted by the president and discussed during a general meeting, the CMS demanded

[8]Morris Wolfe, a Canadian investigative journalist, for instance, recalled receiving "a long poem [from a man] entitled 'Marc Lépine. . . Martyr?'" which argued that "Marc Lépine proved with his life/Feminism has gone too far" [51].

from the NRC "[a]n explicit apology to women and an assurance that NRC pledges to encourage and support women in science" [15], as well as a reprint of the offending issue of the CJP with Freeman's article removed [51]. In this connection, at a CMS General Meeting Asia Weiss brought up the question of whether the presence of a female editor at the journal might have prevented this disaster, noting that the CMS journals had no female editors. [Sherman] Riemenschneider replied that "the Publications Committee is considering the matter and encouraged members to nominate female candidates to these important positions". When [Katherine] Heinrich suggested that the Publications and Nominating Committees "solicit female membership directly", Riemenschneider noted that "it takes an active participation for any change to occur" [18]. Change did ultimately occur, though it took two more years before a woman would join the common board of associate editors of the Canadian Journal of Mathematics and the Canadian Mathematical Bulletin.[9]

On a lighter note, 1992 saw the release of Mattel's infamous "Teen Talk Barbie" dolls, a number of which periodically uttered the objectionable phrase: "Math Class is Tough!" One might dismiss this as utterly trivial to the national mathematical community, yet it was discussed at official meetings of the CMS, as evidenced by recorded minutes. At least one official editorial response addressed the subject (published under the heading "From the Editor... Barbie is Wrong—Math Class is Fun!"), and in it, Robert Rosebrugh expresses the hope that "few people aspire to the stereotyped vision of humanity presented by Barbie and her friend Ken, who, by the way, has never been heard to complain about math class". Describing the reaction from the Canadian mathematical community as "swift and well-publicized" and the reaction by Mattel as inadequate,[10] Rosebrugh notes that the toy giant had promised not to manufacture more dolls but refused to withdraw it from shelves, claiming:

> the offending phrase is one among 270 and that a randomly chosen 4 are on each voice chip, so that the offending phrase is spoken by only one doll in 4,000. Barbie can have some fun figuring out where that 4,000 figure came from.

Members of the CMS executive had reportedly "written strong letters to Mattel Canada requesting that the doll be withdrawn", and CMS officers were instructed "to attempt to secure an adequate response and compensatory actions on the part of Mattel" [19].

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[9]This was Nicole Tomczak-Jaegermann, in 1994.

[10]One might wonder if the same was said about the reaction of the media. In the *Chicago Tribune*, for instance, columnist Bob Greene questioned the response to the dolls by "A women's organization—the American Association of University Women", who found one of Barbie's phrases "deeply offensive". "What was this phrase?" he continued. "Was it a phrase that degraded women and implied that they were merely servants to men? Was it a phrase that indicated women were sex objects? Was it a phrase that said that women were deserving of less money on the job market than men? Not exactly. The phrase spoken by the talking Barbie—the phrase that so outraged the American Association of University Women—was: 'Math class is tough.' " Greene suggested that although in the past, a large company might have "shrugged off" a complaint about a doll that "says something as terrible, as horrifyingly callous", but that "In our politically correct era, [...] Mattel was forced to have its executives make somber statements". [34].

None of this should suggest that the Krieger-Nelson Prize was created directly because of such events, no matter how heinous. These acts that demeaned and attacked women and girls on academic and social grounds, however, catalyzed important discussions of obstacles faced by women and motivated remedial measures to combat them. In particular, the lingering problems of the discrimination against women within the sciences and the social conditions that engendered bias, patriarchy, and misogyny were ultimately addressed head-on.

9.3 Taking Action: The Committee on Women in Mathematics

In November of 1990, on behalf of the Government Policy Committee, CMS representatives met with David Crenna, an "Ottawa expert on the lobbying process" [14]. One result of this full-day meeting was a publication entitled "A Government Relations Strategy for the Canadian Mathematical Society", a consultant report written by Crenna.

The CMS is, in many regards, an advocacy group, and historically has taken an interest in a number of human rights issues including unjust or discriminatory treatment of mathematicians. One key opportunity identified for the future of the CMS was a "project on women in mathematics". Crenna noted:

> Research and simple statistics show that there appear to be important barriers or inhibitions to the advancement of women in the mathematics professions. By undertaking a project in this field, the CMS would demonstrate its social concern, build partnerships with other organizations in the field, including users of mathematics, and address a key vulnerable area of the profession [27].

This report was published in the summer of 1991. By December of that year, an ad hoc "Committee to Encourage Women in Mathematics" was formed "to consider the possibility of establishing a Standing Committee on Women in Mathematics" [16]. At that point in time, there were "at least a couple of people" on the CMS Executive that saw this matter as warranting attention [44].[11] Accordingly, the idea was supported, and the following year, an Executive motion that the CMS establish a Committee on Women in Mathematics (CWM) was carried unanimously [17]; by that point, it had emerged as "an obvious sort of thing" [44]. Its first members would be decided the following year, and included [Asia] Ivić-Weiss (chair), [Lee] Lorch, [Margaret] Beattie, [Véronique] Hussin, and [Nina] Zorboska.

[11] Rosebrugh noted that this "probably should have been done ages before that [point in time]".

9.3.1 The Projects and Ambitions of the CWM

The initial budget for the CWM was to be $500 for the 1992–1993 calendar year, though this was intended to represent a nominal amount for the sole purpose of allowing the committee to get established [17]. The duties and responsibilities of the committee, as approved by the Board of Directors in June 1992, were centered about studying the participation of women in mathematics in Canada, which included the creation of a database of current and historical information on women faculty and graduate students from mathematics, statistics, and computer science departments at postsecondary institutions across the country and reporting back to the Board [12]. The CWM would also "make recommendations to the Society which will increase the number of women in mathematics at all levels, and, in particular, [. . .] encourage the participation of women in mathematical research and teaching" [47]. As for their early agenda, described at the CMS General Meeting in December 1992:

> The Committee has already discussed several possible programs. The first is the establishment of a data base [sic] which would include data on female professors and graduate students at universities, along with their areas of interest. The Committee also discussed the need for a communication network for those interested in the issues. Possible mechanisms include a newsletter and official communications with other associations. One step towards this has already been taken in inviting the new president of the Association of Women in Mathematics, Prof Cora Sadosky, to take part in the informal session. There is a possibility of organizing a joint event, possibly a panel discussion involving equity, etc., for the August 1993 meeting in Vancouver. [. . .] The Committee welcomes ideas.
>
> The Committee is also discussing the need to increase the visibly [sic] of women at CMS meetings. One possibility is to have lectures given by women mathematicians. Workshops involving female graduate students are another possibility.

By August 1993, this ambition had crystallized into a definite form. In addition to establishing a liaison with other institutional bodies, including the AWM, the committee was considering creating an electronic newsletter "*and is also working hard at establishing a lecture series which would feature prominent women mathematicians* [emphasis added]" [22].

It appears that much of the work of the CWM during its first few years was devoted to increasing the number of female speakers at mathematics meetings. As expressed in August 1993 the then CWM chair indicated, "Part of the rationale for gathering the [database] information was to assist meeting organizers in identifying potential female speakers in various areas of research". In this vein, the CWM "was very concerned to see the total absence of female speakers" at the 1993 CMS Seminar held at UBC [21].[12] One notes, however, that a November 1993 call for research sessions for semi-annual CMS meetings in 1995 and 1996 states: "It is CMS policy to actively encourage the participation of female mathematicians" [20].

[12]This issue reached well beyond the Canadian border. It was only in 1990 that the International Mathematical Union resolved "to take into account that many qualified women were available as speakers for ICM 94". This resulted in "the unprecedented number of ten women invited speakers (out of a total of a hundred and sixty five lecturers), two of them delivering plenary lectures" [45].

9.4 The CMS Lectureship for Distinguished Research by Women in Mathematics

Lectureships for women and the issue of women speakers at conferences were evidently on the minds of many CMS members during the early 1990s. When [Katherine] Heinrich asked attendees of the December 1991 General Meeting about the need to increase the number of plenary lectures given by women, [Edwin] Perkins responded that "this has been a concern of the Research Committee, Executive Committee, and Board of Directors" [15]. The minutes indicate that:

> The new Chair of the Research Committee, Dr. Ram Murty, will be contacting organizers and special session organizers to tell them of the concern without imposing any quotas or fixed demands. It is hoped, and anticipated, that this will have an impact on the future list of plenary and sessional speakers. Should no change be observed, then the policy would need to be reevaluated [15].

Additionally, in the midst of the Barbie doll controversy in 1992, it even happened that the Executive of the Board of Directors discussed a proposal from [Carl] Herz about "creating some kind of joint lecture with Mattel" [19].[13] All of this suggests that even if the Krieger-Nelson prize did have particular champions within or outside of this group, in the end it was a project supported and pushed forward by many.[14] Although further information as to any additional motives animating their actions, if existent, would provide a more robust picture of the developments in question, unofficial records appear to have been lost. By all accounts, including the recorded notes and memories of those involved, there was no opposition to the prize itself. It is unclear how many, if any, were more or less indifferent to the idea.

As it turned out, the CMS ultimately moved to establish a different sort of lecture series. At the December 1993 Board of Directors meeting it was moved:

> That the CMS establish an annual CMS Lectureship for Distinguished Research by Women in Mathematics in recognition of an increasing number of excellent contributions by women to mathematics;
>
> that this award be intended for an outstanding female research mathematician, in early to mid career;
>
> that there be no restriction on nationality and that female winners of the Coxeter-James lectureship be eligible for this award; and
>
> that each recipient of this award will deliver a lectureship to the Society at the annual summer meeting [23].

The first of the awards was to be made at the fiftieth anniversary meeting of the CMS in Toronto in 1995.

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[13]While they did not support this venture, they "did agree that Mattel should be placed on the list of prospective donors and approached as part of the 1993 contributions campaign" [19].

[14]It has also been suggested that Christiane Rousseau played a fairly active role in the development of the prize [36]. It has not been possible to verify this. Her name is absent from the discussions in the CMS Notes mentioned here, however, and she did not become the Vice-President of the CMS until 1995.

The CMS already had two named lectureships at this point: the Jeffery-Williams Lectureship and the Coxeter-James Lectureship. These were created in 1968 and 1978, respectively, and exactly one woman had held one of these awards by the early 1990s.[15] As these prizes were well-established, there was reportedly an initial feeling that, in fact, the CMS should simply be ensuring that they were awarded to women. There was a stronger feeling, however, that it was important to do something special [44].

It is noteworthy that although one might expect this new award was the proposal of the CWM, the original motion to create the lectureship came from the Executive Committee of the CMS, and was presented by the chair of the Research Committee.[16] As remarked by [Asia] Ivic Weiss in the June 1994 Board of Directors Meeting minutes:

> [. . .] the decision to establish the lectureship had come very quickly without consultation with the Committee on Women in Mathematics [24].

The primary reason for this seems to be that the Research Committee oversaw the adjudication of candidates for both the Jeffery-Williams and the Coxeter-James Prize Lectureships, making it fairly natural for this group to take over the new prize for women. Aware that the prize had "the possibility of being a high profile award", "the [Research] Committee wanted to establish very high standards" [23]. It was considered particularly important to ensure that the quality of this prize was identical to that of the other two with respect to the contributions of the recipients [46].

This initial lack of communication with the CWM, however, led to certain disagreements about the nature of the lectureship and the pool of candidates to whom it could potentially be awarded. The CWM, for instance, preferred awarding it to someone from Canada, "since the situation for women is not as favourable as elsewhere". However,

> The [CWM] had not wanted to bring their objections to the Board of Directors meeting at that time but hoped that the Research Committee would be open to their input after the fact. They were not trying to be agressive [sic] towards the Research Committee. Indeed they were very pleased with the decision to establish the lectureship but did hope that more input would be welcomed [24].

This issue of nationality was also a concern for others on the Board of Directors. Meeting minutes from December 1993 indicate that [Angelo] Mingarelli and [Lynn] Batten were "concerned about the national issue". Batten would prefer to see the phrase "female mathematicians working in Canada" included, and Mingarelli noted that going beyond Canada's geographic boundaries "might be doing the Society a disservice" [23].[17] In the end, early announcements for the prize explicitly noted

[15]Cathleen Morawetz held the former in 1984, and is the first and only woman to have done so to date. No woman had received the Coxeter-James Lectureship. Lisa Jeffrey would be the first to do so, in 2002.

[16]At the time, this was Nicole Tomczak-Jaegermann.

[17]When the CWM moved that "[t]he lectureship should be primarily directed to women involved in Canadian mathematical life", it was tabled at the June 1994 Board of Directors meeting [24], in

that there was no restriction on the nationality of candidates, though historically, preference has been given to researchers with a substantial connection to Canadian mathematics.[18] As for the research areas treated by potential candidates, in keeping with the extension of the database information beyond mathematics proper, in the initial meeting announcing the award "[Nicole] Tomczak-Jaegermann confirmed that the Research Committee would consider women from computer science and statistics" [23].[19]

9.5 The Search for an Appropriate Name

The first call for nominations for the "CMS Lectureship for Distinguished Research by Women in Mathematics" was made in 1994. It was noted early on by Tomczak-Jaegermann, however, that "the name of the lectureship could possibly be changed", but ought to retain the phrase "Distinguished Research". In this connection, members of the Executive Office intended to "research names of female historical figures in mathematics, possibly the first female member of the CMS or the first female to receive a Ph.D. in mathematics in Canada" [23].

Later that year, in an effort "to attach an appropriate name to this prestigious award" the decision was made to solicit input from CMS members as well, with each submitted name to be accompanied by an explanation of why it was suitable [39]. It is not clear just how many submissions were received by either the Executive Committee or the ad hoc committee charged with the task of gathering information, receiving suggestions, and making recommendations for names to the CMS Board, but the decision was understood as nontrivial [46]. According to the report of the ad hoc committee, at least three possible names were proposed for the lectureship. The Executive of the CMS, having considered the possibilities, proposed in December of 1994:

> That the Prize for Outstanding Research by Women in Mathematics be named the Krieger-Nelson Prize Lectureship, pending consultation with the families.

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spite of the fact that a motion "[t]hat the sentence 'There will be no restriction on nationality.' be removed from the nomination proposing the CMS Lectureship for Distinguished Research by Women" was carried (with 18 in favour, 5 against, and 3 abstentions) at the December 1993 meeting [23].

[18]Nancy Reid, the first winner, was a full professor at the University of Toronto when she won the award, and completed much of her education in Canada. The second winner, Olga Kharlampovich, was born and educated in Russia, but had been faculty at McGill University in Montreal since 1990. The third winner was Cathleen Synge Morawetz, daughter of the Irish mathematician John Lighton Synge (1897–1995) who taught at the University of Toronto from 1920 until 1925. In contrast to the others, Morawetz was born in Toronto and completed her undergraduate degree there before finishing her studies and ultimately settling in the United States at NYU.

[19]This is evidenced by the fact that the first winner was a statistician. The general mindset seems to have been that all were "mathematical sciences" [46]), and the prize sought to support woman in this general area of study.

The motion was carried unanimously [25].[20]

9.5.1 The Krieger-Nelson Prize Lectureship

That the award became the namesake of two women is unsurprising in light of the tradition of "double-barreled" names for Canadian mathematical prizes [44]. The suggestions of Cecilia Krieger and Evelyn Nelson are difficult to trace, however, though certain features of their legacies made them striking candidates. In naming the award, for instance, it has been suggested that the Executive Committee preferred individuals who were not currently active (indeed, Krieger died in 1974 and Nelson in 1987), choosing instead to honour the memories of colleagues who had passed [44, 46, 49]. It was additionally desirable that the women were members of two different generations [44, 46]. Beyond these preferences, both Krieger and Nelson left different but marked imprints on the Canadian mathematical scene.

Cypra Cecilia Krieger (1894–1974) was born into a Jewish family in what is now Poland, and moved to Vienna in 1919 to study mathematical physics at the university there. Persecution of the Jews in the aftermath of the Great War led Cecilia and her sisters and mother to emigrate to Canada in 1920. There, she entered the University of Toronto, where she returned to the study of mathematics and completed her Ph.D. under the supervision of J. Webber. She was appointed instructor in mathematics at the University of Toronto in 1928, Lecturer in 1930, and Assistant Professor in 1942, holding this title until her retirement twenty years later.

Mathematically speaking, Krieger is well-known for translating into English two works that helped advance the subject of topology. These were Wacław Sierpiński's *Introduction to General Topology* and *General Topology*. Her own doctoral thesis was published in two parts within the Transactions of the Royal Society of Canada: *On the summability of trigonometric series with localized properties* in 1928, and *On Fourier constants and convergence factors of double Fourier series* in 1930. In broader terms, Krieger's status within the Canadian mathematical scene is significant. In keeping with the CMS Executive Committee's original proposal, Krieger fit the bill perfectly as the third person, and the first woman, to receive a Ph.D. in mathematics in Canada. For this reason, she was a clear choice.

[20]One may notice the addition of the term "prize" in the title of the award. At the same Board of Directors meeting in December 1994 it was moved (and carried, with one opposed) that the Coxeter-James and Jeffery-Williams awards also acquire the title of "prize"; prior to this, they were "Lectureships" rather than "Prize Lectureships". As for the reasons behind this, it seems that the members of the CMS eventually noticed that mathematicians didn't give out "prizes" to each other, and perhaps they should [46].

The case of Evelyn M. Nelson (1942–1987) is somewhat different, particularly as she was known personally to many members of the CMS committees involved in the creation of the lectureship. As a result, her image and memory meant different things to different colleagues, and hence the reasons for supporting her name varied from person to person.[21]

Nelson, whose parents emigrated to Canada from Russia around the time of Krieger's arrival, was born in Hamilton, Ontario. She, too, entered the University of Toronto, having been admitted into its notoriously difficult Mathematics-Physics-Chemistry Honours Program. She transferred to McMaster University, where she quickly became the star of the undergraduate mathematics program there, and graduated at the top of her class in 1965 [11]. Nelson entered the graduate program at McMaster immediately. Her master's thesis was an original work which was published in the Canadian Journal of Mathematics in 1967, and she completed her Ph.D. in 1970 with a thesis entitled *The lattice of equational classes of commutative semigroups*. This, too was published.

Nelson was a prolific researcher in universal algebra. Over the course of her roughly 20-year career she published over 40 papers that displayed her evolution as a scholar. She also served as the editor of *Algebra Universalis*, gave almost 30 invited lectures outside of Canada, refereed for ten different mathematical journals, and together with Bernard Banaschewski, Carl Riehm, and Günter Bruns, directed a research seminar in algebra at McMaster University since described as "legendary" [49]. Nelson was promoted to full Professor in 1983, and chaired the Computer Science Unit of the Mathematics Department at McMaster from 1982 until 1984. At this point, her health was already deteriorating.

Nelson's untimely death from cancer in 1987 cut short her productive career and came as a great shock to her collaborators and contemporaries; she had continued her work almost until her dying day. Since 1991, McMaster University has held "The Evelyn Nelson Lectures" in her memory and in recognition of her many contributions. She is remembered as a thoughtful, well-liked teacher who took the task of instruction quite seriously [11], and has been described as "an extrovert in espousing mathematics", having spoken in secondary schools and judged competitions on top of her regular duties [49]. Above all else, she was a research mathematician [1], and was single-mindedly devoted to her work [49], much of which was centered about unpacking the differences between finite and infinite algebraic structures, and the properties of various equational classes, which she studied from the perspective of model theory [4].

Not inconsequential to the issue of the naming of the prize, perhaps, both Krieger and Nelson were advocates for and supporters of women in mathematics during their careers. Krieger was active in the Canadian Federation of University

[21] It has been suggested, for instance, that Nelson is remembered for social activism connected to the resettlement of American draft resisters during and following the Vietnam War, and that in addition to her scholastic contributions, these purported actions made her an especially pleasing contender in the naming of the lectureship. This is anecdotal, however, and has not been verified. Others suggest that Nelson's possible activism was inconsequential in this regard.

Women (CFUW), which has historically served to promote social justice and ensure equal educational opportunities for girls and women. In this capacity, Krieger was apparently instrumental in the decision of Cathleen Morawetz, who was awarded the Krieger-Nelson Prize Lectureship in 1997, to attend graduate school. By Morawetz's own testament, when she confided to Krieger during her final year at the University of Toronto that she had planned to respond to a call for teachers in India upon completion of her degree, Krieger was horrified at the thought that Morawetz would not continue her studies. When Morawetz replied that the issue was financial, Krieger (then the Convener of the Scholarship Committee of CFUW) assured Morawetz that she could receive a Junior Fellowship [8].[22] Nelson also "had a special interest in the participation of women in mathematical science", and at times gave presentations on the contributions of women mathematicians [7]. She, too, was socially conscious, involving herself in a number of organizations at McMaster including University Senate and the Orientation Steering Committee [1].[23] She also served on committees within the CMS itself [7], and is remembered as an active participant [38].

In 1995 Cora Sadosky, an American advocate for affirmative action, remarked that achievements in supporting women in mathematics by that point were actually quite modest, though appeared considerable against "the bleak background of a field where women were invisible only a few years ago" [45]. Indeed, both Krieger and Nelson had also suffered their share of professional struggles in spite of their important contributions, as did many of their female contemporaries. As pointed out by Morawetz in 1997, Krieger "lived at a time when the prejudice against women meant that she was for over twenty years not promoted from her position as lecturer" [8]. Similarly, apparently due to "countervailing perceptions of priority", Nelson held a post-doctoral appointment with a later title of "research associate" at McMaster for eight years before receiving a faculty position in the department (though in her case, she was suitably promoted to Associate Professor) [11]. She had two daughters, and after she separated from her husband she raised them alone. This made the usual "bouncing around" of academics impossible for her, contributing to her temporary stagnation as a postdoctoral fellow in spite of her obvious talent; one colleague later remembered "hearing many mildly complaining reports that more than once Evelyn brought her two young daughters into the classroom where they would play near the front of the room or, when somewhat older, would quietly sit in on her classes" [4].[24]

[22]Beyond this, Krieger was apparently socially active. Canada has a history of taking in refugees fleeing oppression, and Krieger, a refugee herself in the 1920s, is said to have cared for a Jewish family which arrived in Canada to escape Nazi Germany. This anecdote, though widespread, is difficult to verify.

[23]In connection with the latter, she evidently took up a special project directed at reining in the initiation rites of residence halls [11].

[24]The issue of childcare for women mathematics has clearly endured. One notes that in 1994, the CWM listed its topics for discussion at an upcoming meeting as: "Changes in NSERC policy and its possible impact of female mathematicians", "Joint activities with AWM for the Summer '95

Accordingly, both Krieger and Nelson are remembered not only for their considerable talents and their humanity, but also their trials and tribulations. In the words of York University mathematics professor and civil rights activist Lee Lorch (1915–2014), who stood among the first members of the CWM, "[t]he Canadian mathematical scene has been enriched by a number of women educated in Canada and by a number from abroad". His aim, therefore, in a lecture on "Women in Mathematics" given at the 50th anniversary conference of the CMS, was to "initiate [. . .] a discussion of the presence and prospects of women in Canadian mathematical life — and of the encouragement and discouragement they have received, of the recognition of special needs and the importance of their presence" [7]. As we have seen, the same dialogue is inherent in and inseparable from the early history of the Krieger-Nelson Prize Lectureship.

9.6 Concluding Remarks and Future Work

The Krieger-Nelson Prize Lectureship was established at a time when key members of the CMS had begun to notice that although the number of valuable research contributions by women in mathematics was increasing, these contributions often went unrecognized, officially or otherwise, by means of academic posts, public lectures, or awards. In spite of affirmative action efforts, it was objectively clear that women were few and far between within mathematics departments, particularly at the full-time faculty level, and there was a noticeable dearth of women speakers at mathematics meetings, though in the eyes of advocates for women in mathematics this was not for lack of qualified individuals.

Beyond statistical data, during this period a handful of highly publicized biases and one case of extreme violence against women and girls in mathematics and the sciences had reared their heads on the national stage, opening a dialogue on the conditions for women in studying and working as mathematicians in Canada, and the means by which certain societal barriers could be torn down. These corrective measures, which sought to prevent women mathematicians from being overlooked by their professors and colleagues, included regular prompts to secure women speakers at meetings, and special awards such as the Krieger-Nelson Prize Lectureship to both honour recipients and draw attention to their achievements.

Accordingly, it seems that the creation of a standing Committee on Women in Mathematics and the suggestion of a dedicated prize for women in the 1990s were both consistent with a social and academic background in which improved prospects for women came to the fore internationally. The impetus for these changes came from several directions, including external government strategy consultants, popular and academic culture, and different subsets and members of

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meeting in Toronto", "Resolution on promoting women in mathematics", and "Issues related to childcare" [48].

the Canadian Mathematical Society itself. In particular, the desire to engage more women speakers at professional meetings was clearly on the minds of many, men and women alike. By all accounts, then, the time was ripe for the establishment of the Krieger-Nelson Prize Lectureship, though it was individual efforts that brought it into being. As for its name, bearing in mind the small set of limitations placed on the potential possibilities, many felt that the attributes of very few candidates could compare with the pioneering journey of Cecilia Krieger and the passion and dedication of Evelyn Nelson.

As is the case for many women mathematicians, Krieger's and Nelson's struggles were and are remembered in addition to their triumphs, and it is for both of these aspects of their careers that their legacies are additionally honoured through the prize which bears their names. Similarly, the very creation of the CMS Lectureship for Distinguished Research by Women in Mathematics serves to reflect this duality of the history of prize, emerging as both a celebration of notable achievements by women and a persistent reminder of both the long, quiet, and generic discrimination historically faced by women within academic settings and the growing desire to put an end to it.

One remaining question is that of the impact of the Krieger-Nelson Prize Lectureship. Future work will develop this theme in three key directions: the possible impact related to increasing the visibility of women at national meetings, in keeping with the aims of the CWM; the possible impact on the careers of recipients and the significance and meaning the prize has come to hold for them; and the possible impact on the situation for women and girls in mathematics on a broader scale.

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Chapter 10
Mathematics, Live! Contemporary Perspectives on a Life and Career in Mathematics

Katharine A. Ott

Abstract This chapter features a compilation of excerpts from interviews with female mathematicians. Ten women at varying points in their career discuss their early interest in mathematics, their professional duties and responsibilities, and mentoring.

Keywords Career advice • Mentoring • Collaboration • Networking

10.1 Introduction

Between 2013 and 2016 I interviewed ten women with advanced degrees in mathematics for the Mathematics, Live! column appearing in the *Association for Women in Mathematics Newsletter*. My goal was to feature women with diverse professional roles and, from within academia, a mix of junior and senior mathematicians from a wide range of research disciplines. The following chapter is a compilation of excerpts from these interviews.

In their own words, these ten women share their motivations for becoming mathematicians and the high and low points of their journey from student to professional; they discuss their research and professional responsibilities and give advice on writing, presenting, and collaborating; and they reflect on the role of mentors in their career or offer some mentoring advice of their own. My hope is that within these passages readers will find both shared experiences and inspiration.

10.2 Sybilla Beckmann

Josiah Meigs Distinguished Teaching Professor of Mathematics, University of Georgia (Figure 10.1).

K.A. Ott (✉)
Bates College, 3 Andrews Road, Lewiston, ME 04240, USA
e-mail: kott@bates.edu

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Fig. 10.1 Sybilla Beckmann

On Research

My interest in math education started as my kids were heading into school. I started to think about the fact that we taught these math courses for elementary teachers, and it dawned on me that these courses are really important yet they were a neglected part of our curriculum. For many years I was involved in a number of mathematics education projects: I wrote my math for elementary teachers book and I was on a lot of national committees. But that is not the same as research in mathematics education. A few years ago I realized that I needed to do research in mathematics education, not math. I always assumed I'd go back to do more math research, but ultimately that didn't make sense for me.

I think that more mathematicians should be interested in what is going on in K-12 mathematics. I feel strongly that all of us who teach math need to see ourselves as part of a big community that spreads across kindergarten through college and even graduate level math teaching. Anything you want to teach at the college level depends on what happens at previous levels. At the college level we are preparing teachers, so they cycle back to those earlier levels. I think it is important for us to realize that we're part of this bigger system. That is not currently the way people are talking about education. Most of the conversations are about K-12 as its own separate thing and college as its own separate thing. I think we need to think more from a disciplinary perspective.

That being said, I don't think that it is necessary for more mathematicians to be involved in mathematics education research. I didn't realize when I started doing mathematics education research just how much there is to know. It is a different discipline, and there is a lot to learn. Just because you have taught math, that doesn't mean that you know a lot about education more generally, or even that you know much about mathematics education. Mathematicians could be better consumers of the existing education research. I think that more of that could happen if there were better connections across all of math teaching.

On Mentoring

A piece of advice that I would like to give young mathematicians is not to be afraid to take a different career path, if that is what you want to do, and not to be afraid to ask for what you want. When my kids were young, I asked to be allowed to work part-time, and I taught-part time for about 9 years while holding onto my tenured position. I think there were three different department heads over that time period and not one of them ever said no.

10.3 Misha Kilmer

Professor of Mathematics and Adjunct Professor of Computer Science, Tufts University (Figure 10.2).

On Becoming a Mathematician

By the seventh grade I had that poisoned brain that said, "Math is bad, and it's hard, and algebra is going to be really, really hard." My father was in the Navy so we moved around a lot, and when I started eighth grade we had moved to a new place and a new school. They wanted to give me a pre-test in math and I placed into algebra in eighth grade. I was horrified. It turned out that I loved it. I thought it was fantastic. From that point on, I just loved math. When I was in high school, back

Fig. 10.2 Misha Kilmer

in the day, they were just starting computer classes and I was learning computer programming in Pascal. I thought it was great that I could write programs and see the results in front of me. I knew that I wanted to do something that was math and computer science combined when I got to college.

The Triumphs

A highlight of my career was getting tenure. There was a surprise with that announcement, which was that I was promoted directly to full professor. I hadn't even known that my department had put me up for that. I got this letter from the Tenure and Promotion Committee that said, "Oh by the way, we're recommending you for full professor." That was a real high point. Graduating my first PhD student was another high point, and now she is in a tenure track position doing quite well for herself. I have a bulletin board in my office where I keep thank you notes from students and little mementos; that just reminds me of why I am doing what I do.

The Challenges

The transition from postdoc to assistant professor was difficult. In fact, both the graduate student to postdoc and then assistant professor transitions were hard because you are weaning yourself from your adviser relationships. Suddenly it's you and it's your ideas that count and you have got to drive the project forward. At the same time, because I hadn't had a lot of teaching experience before I came to Tufts, I was worried about preparing lectures and making sure that I did well in front of the class. I did something stupid during this difficult period, which was I had it in my mind that I had to go it alone and therefore I shouldn't be contacting my former advisers for help. I was not giving myself good advice there. I think you should feel like you can reach back to those people. They want to be there to help you when you need a sounding board in those first few years.

On Research

I work in numerical linear algebra. A lot of the applications of my work have to do with some type of inverse problem or image and signal processing. More recently, I have begun getting into tensor based research and work in multi-linear algebra. I get to interact with other researchers and with students, and I get to work on very interesting research problems that have components of mathematics, but also computer science. The applications are terribly interesting, such as image deblurring, blind deconvolution, and medical image reconstruction.

A lot of my research is interdisciplinary. I have joint grants with people in Electrical and Computer Engineering, for example. Our research groups, including our students, will get together each week and talk. These meetings facilitate communication across the disciplines. You have to know the right questions to ask in order to distill the right level of information. Interdisciplinary communication is both written and oral. If you are going to write something down for a broad community, you need to be able to explain to the various communities why they should be interested in what you are doing.

10.4 Tamara Kolda

Distinguished Member of Technical Staff, Sandia National Laboratories (Figure 10.3).

On Becoming a Mathematician

I have loved math since childhood and especially remember attending a variety of math and computer summer programs as a young girl, including a sleep away camp at NASA Goddard Space Flight Center in Maryland. One computer camp had only three girls out of 20 participants, but the NASA camp was better—it was half girls and half boys, probably because of the sleeping arrangements (an old-fashioned dorm split down the center and meant to house girls on one side and boys on the

Fig. 10.3 Tamara Kolda

other). I really enjoyed these experiences but somehow did not view math as a viable career option. I thought about biology until an ill-fated research experience with copepods (tiny water fleas) during my last year in high school. I settled on math in my first year of college, mostly as a placeholder until I could find something better. As you may guess, this never happened, and I continued on to graduate school based on the encouragement of my professors as well as my complete ignorance about the many excellent job options at the bachelor's degree level. Looking back, I feel fortunate to have found my passion early in life, and I am very glad to be alive at a time and in a place where women can pursue careers.

On Research

I do research in computational science, mathematics, and data analysis. My job is focused largely on developing algorithms, which includes everything from theoretical foundations to computational implementations. I have worked in a number of areas including optimization, linear algebra, nonlinear solvers, graph algorithms, and parallel computing. My current specialty is tensor decompositions, which is the generalization of matrix decompositions from 2-way to n-way data for $n \geq 3$. I consider the mathematical formulation of the problem as well as its application. My recent work has considered how improved statistical assumptions change the method and enhance the results.

On National Labs

At a government-sponsored national lab like Sandia, the research is more applied than in academia. Our researchers solve vexing national problems by writing software for simulations, conducting physical experiments, designing and executing studies, and so on. Some lab researchers, like me, have a pseudo-academic research career in that they regularly publish research papers and participate in professional service. In contrast to academia, national labs are highly interdisciplinary and not divided by discipline. To the contrary, our researchers tend to be grouped by the application, and affiliations can and do change over time. As a lab, we are united by a unity of purpose in serving the public interest.

On Writing

When writing, I focus on making a meaningful contribution to science. I am careful in my writing, considering all matters great and small from the overall organization to the correctness of the grammar and even the format of the bibliography. I also invest time in crafting useful illustrations and graphics. I take the feedback of referees seriously, especially the ones that are the most confused. Nevertheless, I still endure my share of rejections. On two different occasions, however, I received a best paper prize for a paper that was previously rejected. Now I say that rejection is the first step to a paper prize!

On Mentoring

Mentors have been critical at every step in my career, especially my PhD adviser, my coauthors in my early career, and my first boss at Sandia. I still ask these people for advice today! I also benefited from specialized workshop-style activities where leaders in the fields shared their career advice on topics like networking, job hunting, presenting talks, etc. I continue to work with new mentors today, though they are now primarily peer mentors—some older and some younger—with different experiences and perspectives. I also enjoy being a mentor myself, doing my part to pay it forward. My mentoring is primarily focused on issues of communication. For instance, I have a talk on “How to Give a Talk” that is available on my web site. Communication is a topic that is lamentably lacking in science education and seems to be the source of most problems. Communication in writing, communication to audiences, and (mis)communication with colleagues are topics that come up over and over again in my mentoring discussions.

10.5 Loredana Lanzani

Professor of Mathematics, Syracuse University (Figure 10.4).

On Becoming a Mathematician

I don’t have a specific memory of a “Eureka” moment so to speak, but I have this clear recollection that as a kid mathematics felt like a safe haven, because with math you were assigned problems and you could either solve them or you could not. There was no ambiguity. I grew up in Italy at a time when there was a lot of uncertainty in the country. There were terrorist groups. The Prime Minister was kidnapped when I was in middle school. Math was one of the rocks, a grounding subject, and I guess that sort of stayed with me.

Fig. 10.4 Loredana Lanzani

The Triumphs

It was not until I was a faculty member at the University of Arkansas (in fact I'd been there for a while), and I started to interact with the students through student activities, like the Women in Mathematics group, that I felt that I had a concrete sense that I was actually making a difference in these students' lives to some extent. And then, my first PhD student defended her thesis and she completed her work. From that point on things really started to get better. You see results, and that is very gratifying. Getting to the point where you start seeing results may take a long time, so perseverance is a quality that one has to cultivate. These recent years, I have to say, have been the most rewarding years so far.

On Collaborating

A successful collaboration requires a combination of factors. There should be some intersection in terms of expertise, but also enough distinction in the expertise so that there is no complete overlap. There also has to be a good match of personalities. For instance, I don't enjoy competition, so when I collaborate with someone we really collaborate—we're not competing against one another, which is not always the case.

Go to lots of conferences and don't be shy in approaching people and just chatting with them. As a graduate student, in fact not just as a graduate student but even as an assistant professor, I always had this sense that I never knew enough about a problem to confidently talk about it with someone else. So I really had a hard time, I had to push myself to go out there and start talking with people. But that is how I started most of my collaborations, just going to a conference, listening to a talk and finding it interesting, and then making an effort to introduce myself to the speaker and just chatting. From there you get a sense of whether you get along with a person, as I was saying before, and typically if the personalities get along then eventually you will find an interesting problem.

On Submitting Research Proposals

Keep in mind that not to be funded is not a synonym of failure, or of doing research that is not interesting or compelling. At the end of the day, the problem is that there is only a certain amount of money that can be spent and that the policy of the National Science Foundation is to fund only a very small percent of the research, this is regardless of the quality.

Another thing that I want to share, from personal experience, is that when I write a proposal and it gets funded it's great—but that won't happen all of the time and it's not an outcome I rely on. On the other hand, one outcome that I know for sure will come out of the process, and which depends only on myself, is that anytime I write a proposal by the end of the experience (which I always find excruciating!), I have a much better understanding of my own research program, to an extent which I didn't even dream of when I was starting to write the proposal. That is something that has happened to me every time, and that I have come to rely on.

10.6 Karoline Pershell

Lead Data Scientist at Zenti, Inc. and Director of Research and Strategy at Service Robotics and Technology (Figure 10.5).

Fig. 10.5 Karoline Pershell

On Becoming a Mathematician

I was going to study political science, because I thought that in order to save the world I needed to rule it! I started off at Saint Mary's College, which is the all-women's sister school to the University of Notre Dame. I took a few political science classes and felt that I didn't have the network or connections to go with politics. At the time I had a math professor who was a nun. She told me I was really good at math and that I should do math. I thought, this is someone who has absolutely no ego, and who is doing math just because it's wonderful, and I decided yes, that's exactly what I want to do!

I probably didn't think it through at the time, but in retrospect what this story really highlights to me is that around the college age it's very important to tap people on the shoulder and say, "You probably don't see it yet, but you actually could come be part of this club." Math is intimidating. We see our professors, particularly older ones, who have been there a long time. We might not feel that could be us one day. We really need that direct invitation. And, sometimes we need to hear it throughout each new stage in our career.

On Work

I am Lead Data Scientists at Zenti, Inc., where I am also a member of their Scientific Advisory Group. I am also Director of Research and Strategy with Service Robotics and Technology (SRT). Zenti, Inc. does data mining of social media data. I work with optimization of the back-end algorithm and I work with the client to help them understand how to understand their client, the client's characteristics, and how we can identify those characteristics through language in social media.

I can give you a specific example. We've been working with Dr. Joe Franklin, a professor at Florida State University. He is in the Psychology Department and he focuses on suicidal behavior. The language associated with suicidal behavior is well documented medically. What we have done is to create natural language processing classifiers that can review Twitter data and identify these kinds of languages. Zenti's system will then show the user a red flag, meaning that it has identified a Tweet that is really high on one of our scales (like hopelessness), and then we can review that person's history and determine if they appear to be at risk.

I do think that being a math professor helped me in my current position in the following way: When you're a math professor, you teach everyone, including the art students who don't want to be there. What I've gotten good at and what has helped me with these jobs is my ability to transfer technical information to a non-technical audience so that they care about it.

On Mentoring

When I was in academia, I would tell my students that the most amazing thing about being a student is the summer. Never again are you going to be able to take a job for two or three months and then quit and not look like some sort of irresponsible person. It's important to take advantage of the summer to get experience and exposure to as many different types of people as possible. I know that when I did those summer experiences, they always resonated, they always gave me something different to talk about, and they always opened up my thinking. I would really encourage students, if they have the opportunity, to look beyond academia and to at least try these things, even if they know that in the end they want to be a professor.

10.7 Sonja Petrović

Assistant Professor of Applied Mathematics, Illinois Institute of Technology (Figure 10.6).

On Research

My field of research is at the intersection of two seemingly unrelated areas: one is commutative algebra and one is statistics. It seems like they are very much disconnected, however it turns out that a few decades ago a connection was made that made it clear that if you are proficient in both fields, you can go very far.

Fig. 10.6 Sonja Petrović

From that point on, the use of computational algebra was promoted in statistics as a new tool where the traditional statistics methods do not apply. The field uses commutative algebra, algebraic geometry, and some very recent statistical methodology research and data analysis tools.

I started in algebra. I had not even taken a statistics class since my undergraduate days, because it was a different department and it didn't seem like a feasible thing to do at that time. I kind of kept up-to-date with the topics a little bit, because I thought this was something that I should know. Then I went to a conference at the Institute for Mathematics and its Applications (IMA) and gave a poster. A prominent statistician, Stephen Fienberg from Carnegie Mellon, apparently saw my poster. He gave the closing talk at the conference. As part of his slides he made sure to incorporate almost every topic he had seen throughout the conference, including my own. He wrapped together the topics of the conference from a statistician's point of view, which was very useful for everybody who was not a statistician at that conference.

I made sure that I sat close to him at dinner, together with a friend who I had just met who was his former student. We chatted about things and I asked, "Can you tell me about these things you said my work was relevant for?" He told me, and I had no idea what he said. I tried to ask for more of an explanation, and he gave me some definitions and I was still lost, so I wrote it down and I went home. I emailed him a few times asking for references. Eventually he said, "All right, just fly over here and spend the day and we'll talk." So I went there and I thought, "I have got to learn statistics!" This is how I started transitioning into using both fields.

On Mentoring

I was really pushed quite a bit along the way by various mentors. Everything I have and everything that I can do, I think I owe it to those people. Some of them, like my PhD adviser Uwe Nagel, are people who were obviously helping me along the way. But also just talking to various people who are more senior than me at various stages, that has helped me tremendously. I work with people who are younger than me academically and I work with people who are much more senior than me academically, and it's nice because you can learn things from all of them. If you let them all push you along, they will. That is just how math works. It's collaborative; you can learn from your students, your advisees, our advisers, and your colleagues. You can learn from everybody!

10.8 Karen Saxe

DeWitt Wallace Professor of Mathematics, Macalester College and Director of the Washington DC Office of the American Mathematical Society (Figure 10.7).

Fig. 10.7 Karen Saxe

On Becoming a Mathematician

I went to college at Bard College in New York. I knew that I wanted to do science, and at first I thought that I might want to do chemistry or physics. I started out in calculus, physics, and chemistry. I liked calculus pretty well, and I did really well in it and the teacher thought that I should take linear algebra the next year. I took linear algebra and that sealed the deal. I majored in math and physics, and at the end of junior year I knew I was going to get a PhD, but I wasn't sure whether I should apply to math or theoretical physics departments. I don't remember how I made the decision but sometime over the summer I decided to go to math graduate school. I applied, and chose to go to the University of Oregon, which turned out to be a great match for me.

I was pretty sure I wanted to end up teaching at a liberal arts school, but I thought that I should apply for research postdocs. Things were a little different then than they are now. It was not the case that you really needed to do a postdoc to get a job at a good liberal arts school, which is more standard now. I ended up taking a FIPSE (Fund for the Improvement of Post-secondary Education) post-doctoral fellowship at St. Olaf College in Minnesota. That was terrific because I taught one class each semester and had a budget for travel and books. I had a great mentor at St. Olaf College, Paul Humke, who brought us every week to the University of Minnesota and we would talk with people. It was a two-year postdoc, so then I applied to liberal arts schools.

On Work

Our department is a joint Math, Computer Science and Statistics Department. We have about 15–20 people. Of the tenure stream faculty, four are computer scientists, two have statistics PhDs, one has an applied math PhD, one an electrical engineering PhD, one a biomedical physics PhD, and five of us are theoretical mathematicians. We are the biggest department on campus. We offer three majors: Math, Computer Science, and Applied Math and Stats. We teach five courses a year. Because we are such a big department, those teaching math can almost always count on only two preps in a semester. We really do require an active scholarly portfolio, so you do have to publish. It's different throughout your career, but to get tenure you have to publish, and you have to continue to be active throughout to get promotions.

The students at Macalester are terrific, and so is the faculty. There is a center for scholarship and teaching on campus, and every week a faculty member gives a talk about what their current research is. One week you go in and you hear from a painter, and the next week you are hearing from a physicist. It's very casual, but you can ask all kinds of questions about these things. And you really get to see what everybody is doing and sharing. From what I have seen, you don't typically get that at a university.

10.9 Diana Thomas

Professor of Mathematics and Director of the Center for Quantitative Obesity Research, Montclair State University (Figure 10.8).[1]

Fig. 10.8 Diana Thomas

[1]Diana Thomas is now a professor of mathematics at the U.S. Military Academy, West Point, NY.

On Research

I am at the interface of mathematical methods and obesity research. Right now, I don't have a particular area of math that I apply. The researchers in obesity drive the problems. They have problems that they are interested in solving and I either utilize what I have in my toolbox, or I might have to learn something new, or I might reach out and talk to a statistician. Sometimes the math that you need is very simple, and sometimes the math that you need is more complex.

Obesity research is not like math biology where there is an actual field titled "math biology." I think it is pretty hard for an early career investigator to do this kind of research because they are going to have to wander out of a well-defined discipline and take some risks. Mathematicians need to get tenure and they need the support of their department. The department might decide that this type of research is not really mathematics. Likewise, it may be difficult to break into a different field to publish and apply for grants when you are housed in a mathematics department, so there is professional risk involved. I think that mathematicians can bring a lot to the obesity research field but only when they feel secure themselves—when they are close to tenure, or tenured. Indeed, I was just tenured when I started this line of inquiry.

The Challenges

The switch from mathematics to obesity research was hard. When I made the switch it was over a period of time starting in 2008, and I'm probably still making the switch in a lot of ways. I know how to do things in math and I would say that I have a place in math. I used to direct the undergraduate poster session at the Joint Mathematics Meetings, and I'm in a math department, and so I knew what my professional identity was. All of a sudden to have my papers rejected by math journals that say it's not math, and then to turn around and get them rejected from the medical world as well was difficult. I was working like I've never worked in my life—long, long hours, and long, long days to the point that I eventually got sick—and to not have any product from it, some days I just felt like quitting. I definitely have come over that bump. I have figured out how to speak to a multi-disciplinary audience and how to publish in the medical and nutrition journals.

On Giving Presentations

I had to bomb a few talks before I learned. In mathematics we have a very laid-back way of presenting. It involves going to the chalkboard and interacting with the audience so that they can ask you for more detail. With medical audiences, they need to get what you are doing in three seconds or less or they may give up. This is because they are busy in a much different way than mathematicians. Their publication rates and grant demands far exceed that of professional mathematicians. I learned to explain technical material in sound bites. I practiced and practiced to hit the mark and to make sure that I can deliver what I have to say quickly. This skill touches areas well beyond my research. It has positively impacted my classroom delivery as a teacher, and it works well with trying to clearly articulate points to administrators.

10.10 Amanda Tucker

Assistant Director of Undergraduate Studies, Department of Mathematics, University of Rochester (Figure 10.9).

On Becoming a Mathematician

I was way into math before high school. My dad is a mathematician and computer scientist, so I have a long-standing history with math, well, with math and science. I spent a summer in Boston at PROMYS (Program in Mathematics for Young Scientists), and that summer was the first summer that I really loved math more than I loved science. I fell in love with math, I fell in love with number theory, and

Fig. 10.9 Amanda Tucker

I fell in love with Boston. I ended up going back to MIT as an undergraduate and then later became a counselor for several years at PROMYS, then a head counselor, and I even went back after I finished graduate school as a research mentor.

On Work

I teach two classes in the Fall and two in the Spring, along with some additional duties. I do undergraduate advising, advise the undergraduate Math Club, organize GRE prep, and I will be helping graduate students with teaching. I will help grad students prepare teaching dossiers and watch them teach, and other things to help prepare them to teach courses both at the University of Rochester and beyond.

On Teaching

I try to think about what I can do that is best for my students and how I can help them the most, while also staying interested myself. Learning new stuff and teaching new stuff all of the time is what keeps me happy. If you feel stagnated at all, or are interested in something but intimidated about learning something new, my advice would be to look at the wealth of online courses out there. I probably signed up three different times for this online course on big data. Twice I failed to really complete the class, but then I signed on to teach a class and so the third time I finally completed it. Volunteering to teach something that you want to know about is a great way to learn a new topic. If you are a graduate student, maybe think about doing a reading seminar where you know that you are going to have to lecture on the topic every other week. You never know how your career is going to unfold, but almost anything that you teach yourself that interests you, you will manage to work into your career down the line.

On Mentoring

I would say, especially to graduate students or new PhDs, to find collaborators. Find many of them, find them young, and find them right away. When I look around me, I feel like the happiest, most successful mathematicians, especially the happiest, most successful female mathematicians, are those who have really good collaborators. And there is no better time to form collaborations than when you are in graduate school. It can sometimes seem kind of daunting as a woman to initiate collaboration, but stick it out.

10.11 Ulrica Wilson

Associate Professor of Mathematics, Morehouse College (Figure 10.10).

On Becoming a Mathematician

I remember the first time that I got really excited about solving problems, and that happened during a mathematics class. I very much associated solving problems with doing mathematics. It was in sixth grade and my math teacher would do these puzzles. I remember not knowing the answers, and I remember the process of thinking hard to try to figure it out. It taught me that mathematics was more than formulas and plugging and chugging. From very early on I thought of mathematics as problem solving and that is what I enjoyed.

At some point during college, with lots of influence from faculty, I decided to go to graduate school to get a PhD in mathematics. This probably happened after my first summer research experience, and getting feedback from faculty that I was capable of being a mathematician.

My thesis was in algebra, specifically non-commutative rings. I've never been particularly interested in the applications of mathematics. I very much like the abstractness and the richness of the theory of pure mathematics. To some extent, algebra found me. When I was taking the first three semesters of algebra at Emory I got along well with the professor teaching the courses. I spent a lot of time in office hours and then ended up doing a reading course with him. Really, what happened was that I wanted to work with Eric Brussel and it turned out the kind of math that he did was interesting, too!

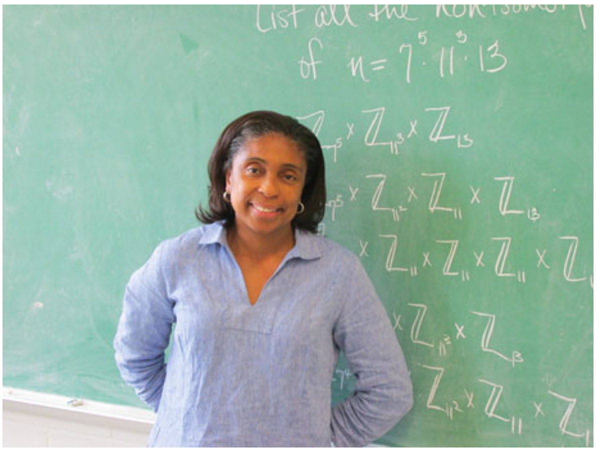

Fig. 10.10 Ulrica Wilson

On Balancing Teaching, Research and Service

I have strategies to balance the demands—whether or not they work is a good question! I try to do just one thing at a time. I block out periods of time when I am doing administrative work, and I give myself permission to not do administrative stuff outside of that time period. One thing I can't control is the teaching duties. I have to be responsive to that, whenever it comes through and whatever that means. All of the other responsibilities I can compartmentalize pretty well. For the research piece, I do spend more time on that in the summer and over breaks. I often go and visit a collaborator right after the fall semester ends and before Christmas. That way I have something going on over the Christmas break that is research related.

On Mentoring

I think even today it has been really helpful for me to have mentors for all kinds of things. One thing I want to say about mentorship is that most of the people who I think of as mentors probably don't know I think of them as mentors. I think people get a little worried about what that title of mentor means. All that it means is looking people in the eye, answering their questions, letting them know when they are messing up, and giving them a path to get back on course.

10.12 Mathematics Is Alive

We should strive to learn the stories of more contemporary women mathematicians and share these stories with colleagues, students, and the general public. This is just one small way that the mathematical community can encourage more women to study advanced mathematics. For those of us already in graduate school or holding advanced degrees in math, a broader awareness of the spectrum of who does mathematics, what those individuals do, and how they progressed through critical career transition points will empower us individually and lessen the impacts of implicit bias and stereotype threat.

Part II
Biographies of Individuals

Chapter 11
Florence Nightingale (1820–1910): A Pioneer of Data Visualisation

Noel-Ann Bradshaw

Abstract In this chapter Florence Nightingale is positioned not just as a mathematician and statistician but also as a forerunner of the modern-day areas now known as operational research and data science. The chapter begins by examining the influences in Nightingale's early life which led to her interest in, and aptitude for, mathematics and statistics. A selection of the various detailed data charts that she created in order to influence political decision making is discussed. Following on from her charts, Nightingale's commentary on some of the statistical calculations and data management by army officials during and after the Crimean War is presented and there is discussion on the enormous impact of her work on the mortality rate of soldiers in the British Army and her subsequent significant influence on the reorganisation of army medical statistics.

Keywords Florence Nightingale • Statistics • Data analysis • Statistical figures • Operations research • Data science

11.1 Introduction

For most people today the name "Florence Nightingale" will conjure up a picture of "The Lady with the Lamp" in the Crimean War (1853–1856) and bring to mind her contribution to nursing. However, whilst she was indeed heavily involved in practical nursing, her contribution to the medical world went far beyond these nursing skills and even the training of new nurses [2]. Her knowledge and understanding of mathematics and the correct use of statistics led to her being able to comment usefully on the numerous inaccuracies in the data that were collected and reported on during the Crimean War. Her ground-breaking work in this area continued after she returned to England and, as a result of her influence, great changes took place in the organisation and reporting of British military statistics both in the UK and in the British colonies [15]. Her work did not end with the armed forces. She also

N.-A. Bradshaw (✉)
Old Royal Naval College, University of Greenwich, London, UK
e-mail: N.Bradshaw@greenwich.ac.uk

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Fig. 11.1 Portrait of Florence Nightingale [40]

played a pivotal role in the improvement of conditions for those in workhouses and for the working classes in general. It was her unusually deep understanding of data and statistics that led her to set up various training programs for nurses and district nurses in England [18]. This chapter will examine how Nightingale (Fig. 11.1) used her quantitative skills to bring about change to the areas of society about which she was so passionate.

11.2 Early Influences

> I can never be sufficiently thankful to Papa for having given me an interest in Statistical and Political matters [24].

Florence Nightingale was born in the city of Florence, Italy, on May 12, 1820, to William and Fanny Nightingale. Her sister, Parthenope, had been born in the previous year in Naples. After Florence's birth, the family moved back to England. They initially settled at Lea Hurst in Derbyshire but then purchased an estate, Embley Park, in Embley, Hampshire, where they ended up residing during the winter months as Fanny found the Derbyshire climate too harsh. William Nightingale had been the recipient of a large inheritance at the age of 10 so did not need to work in order to support himself and his family [1]. The family was highly regarded amongst the upper echelons of society and, as a result, they mixed with intellectuals and political movers and shakers of the day including Charles Darwin and Lord Byron [1]. The noted Nightingale biographer, Mark Bostridge [1], added that Byron's daughter, Ada Lovelace, was befriended by Nightingale and her sister, and a contemporary biographer, Edward Cook, reproduced a poem that Lovelace wrote about Florence, "Should war's dread strife its victims claim" [3].

Nightingale was an avid letter writer from a young age. Many of her letters still exist and show the sort of upbringing and education she had. She appears to have been a quite studious child with a keen sense of fairness and a head for order and number. An example of this is a letter written when aged 8 to her grandmother after a trip to a zoo in which she listed all the animals she had seen and recounted how many there were of each species [22]. In a letter to her sister, who was away with their mother, she described the organisation of the pantry and tabulated how certain fruits and vegetables were categorised [23].[1]

Nightingale's education was supervised by her father, who was keen that both his daughters should learn academic subjects as well as gain the variety of accomplishments, such as drawing and needlework, that Victorians expected of females in society. She had a great passion for learning; several of her early letters to her mother and sister are written in French and testify to her language skills [20]. There are many anecdotes from friends and family members mentioning her accomplishments in Latin and Greek. A particularly nice example is recorded in the journal of a cousin of the social reformer Elizabeth Fry. It describes a dinner party where the man sitting beside Nightingale was heard to comment afterwards, "a capital young lady that if she hadn't floored me with her Latin and Greek" [1].

When Nightingale was about 18, her sister wrote: "Florence has taken to mathematics - and like everything else she undertakes she is deep in them and working very hard" [1]. Like many mathematicians, it seems that Nightingale put her all into her pursuit of the subject. Bostridge [1] described an occasion where her cousin Henry Nicholson (who was studying mathematics at Trinity College, Cambridge) came to stay at Lea Hurst while the family were in the process of moving to Embley Park. Oblivious to the chaos around them, Nightingale and Nicholson "soon became absorbed in logarithms" [1].

This interest in mathematics led Nightingale to read and comment on the work of Lambert Adolphe Jacques Quetelet, the Belgian statistician whom she was to eventually meet in 1860, when he chaired the International Statistical Congress (ISC) in London and after which they kept up a lively correspondence [5]. What initially started as an interest and a pastime was later to become a pivotal tool which Nightingale used to gain influence and bring about change.

[1]These and many other letters can be found in the collections at the Wellcome library [40] or read online via Professor McDonald's project: *The Collected Works of Florence Nightingale* [21].

As a young adult Nightingale struggled with depression, possibly caused by a lack of a perceived purpose. She wanted to work and do something more with her life rather than settle for getting married and having a family. This ambition was frowned upon by her parents and other family members [1]. She had taken part in several trips to the Continent and it was while in Germany that she spent some time at a hospital in Kaiserswerth. Here she developed a friendship with the Lutheran pastor Theodore Fliedners who had established the Institution of Deaconesses, which included a hospital, some years before [1]. From working with Fliedners and his second wife Caroline during several prolonged visits, Nightingale learned much about nursing and hospital management [1]. As a result of this training, she put forward a number of proposals for a career in nursing to her parents. However, they were initially unsupportive as nursing was generally not thought to be a respectable profession and especially so for someone of their social standing. It was also on one of her continental trips that she met Sidney and Elizabeth Herbert, a couple who were going to greatly influence the course of her life [1].

Despite Florence being very close to her sister when they were young, their relationship became strained as they grew older and eventually, for the sake of family peace and Parthenope's health, it became necessary for Florence to live independently. Reluctantly, her parents allowed her to work as the superintendent of a home for gentlewomen in London's Harley Street in early 1853 [1]. Not long after Florence had gained independence from her family, the Crimean War broke out in October 1853. Florence immediately wrote to Sidney Herbert (who was then Secretary at War) offering her services, while at exactly the same time Herbert wrote to Florence asking (or, according to Parthenope, "entreating") Florence to travel to the Crimea and assist in tackling the medical chaos which was just starting to be reported [3].

The remainder of this chapter will show how Nightingale used her time in the Crimea to gather the evidence and experience which enabled her to help reorganise the medical statistics in the British Army and to make a huge contribution to government policy and public understanding of statistics and data management. Nightingale's nursing work and her reorganisation of supplies in the Crimea will not be discussed as there are many detailed accounts of this elsewhere, such as [1] and [19].

11.3 The Use of Visual Representations

Diagrams are of great utility for understanding certain questions of vital statistics [29].

Nightingale was in the Crimea for just under two years, from Autumn 1854 to Summer 1856. In this short time she managed to reorganise the military hospitals and oversee the arrival and work of the Royal Commission on the Sanitary Condition of the Army in March 1855 (headed by Dr. John Sutherland who was to become one of her closest advisors). She was subsequently asked to contribute to the Royal

Commission's final report. Whilst in the Crimea she communicated with many influential people in the British government and society in order to highlight the plight of the soldiers and to raise awareness of the poor organisation of military statistics [1].

Shortly before Nightingale left the Crimea she became ill. This illness never left her and she remained an invalid until her death in 1910. Some of her biographers have referred to her as a malingerer as there was no documented diagnosis of her condition, but others say that her reported symptoms suggest that she is likely to have suffered from brucellosis [6] or spondylitis [1]. However, despite her illness, and days when she described herself as "entirely a prisoner to my bed" [27], throughout the remainder of her long life she produced numerous papers and reports and successfully lobbied government on a wide variety of issues – from the health of the British Army in England and India to the condition of the poor and mentally ill living in workhouses [1].

In Autumn 1856, just after her return from the Crimea, as a result of an audience with Queen Victoria and a subsequent meeting with the new Secretary of State for War, Lord Panmure, Nightingale was asked to draw up a list of potential members for a new Royal Commission to investigate the state of the British Army's whole medical department both at home and abroad [1]. Panmure also requested her to write a confidential report to enable him to "further her views" on the sanitary requirements of the army [36]. The result was a lengthy report, *Notes on Matters Affecting the Health, Efficiency and Hospital Administration of the British Army* [30], accompanied by a pamphlet mainly containing diagrams and tables of data [29] which had been reproduced from the appendix to the Report of the Royal Commission. Initially confidential, it was later distributed to a variety of public figures [19] but not formally published [12]. The first draft of the report was 567 pages but a later preface by Nightingale indicates that she received a large amount of new material which she inserted into the beginning of several chapters. The original pages of the report have Arabic numbers but the additional pages have Roman numerals which are duplicated in each section. The resulting 853 pages, as McDonald noted, are "extremely difficult to follow", but nonetheless make for fascinating reading [19].

Nightingale's pamphlet of diagrams, referred to by Herbert as her "Coxcomb" [35], was publicised more widely. In a letter to Herbert on Christmas Day 1857 [26], she concluded that she didn't think anyone would read the tables and diagrams, despite her foreword to the Coxcomb saying, "Diagrams are of great utility for understanding certain questions of vital statistics by conveying ideas on the subject through the eye which cannot be so readily grasped when contained in figures" [29]. Yet she went on to compile a lengthy list of categories of people who should receive it, including Queen Victoria.

Nightingale was aware of William Playfair's use of diagrams to persuade and campaign within the commercial world [11]. Playfair's pie charts and line graphs seem to have influenced Nightingale's use of what are now known as infographics. Her main report contains the three well-known polar area diagrams known to Nightingale as "Wedges", two of which are reproduced here (Figures 11.2 and 11.3).

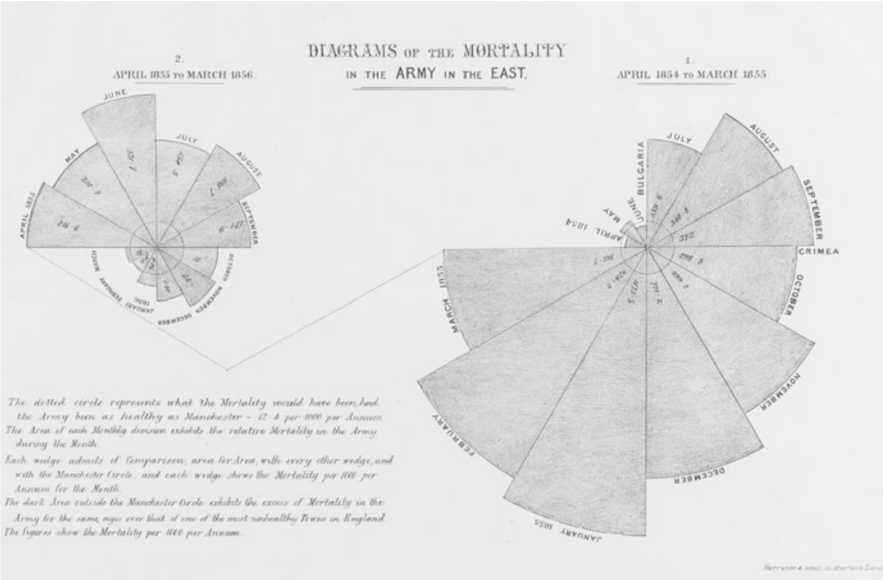

Fig. 11.2 Diagrams of the Mortality in the Army in the East [40]

These polar area diagrams were already being utilised extensively by Quetelet and André-Michel Guerry (a French lawyer and statistician) and were commented on and reproduced by Friendly [9]. It is interesting to note that the data Nightingale depicted works particularly well when portrayed in polar area diagrams, but, because of the large range of the data, they do not transfer well to the bar or line graphs that Nightingale used elsewhere. It would also be very difficult to clearly show the comparison with Manchester in Figure 11.2 on a standard pie chart.

In Figure 11.2, Nightingale has graphed the mortality rate from April 1854 to March 1856. The inner circle on each polar diagram represents the average mortality rate in Manchester, which Nightingale referred to as "one of the most unhealthy towns in England". This comparison immediately grabs the reader's attention and cleverly illustrates the extent of the problem in the Crimea. The diagrams in Figure 11.2 show that after the introduction of the Sanitary Commission, from March 1855, the mortality rate started decreasing.

In Figure 11.3 Nightingale has used the same underlying data as in Figure 11.2 but this time she has introduced coloured wedges to compare the different mortality rates from different causes of death. The blue wedges represent deaths from zymotic diseases (such as cholera and typhoid), the red wedges deaths from wounds and the black wedges deaths from all other causes. All wedges are measured from the centre.

The Coxcomb also contains two diagrams that Nightingale referred to as having large areas that looked like "a great black bat's wing" [29]. However, Nightingale realised that the diagrams in Figures 11.4 and 11.5 were open to misinterpretation and later editions of the Coxcomb contain a note emphasising that, in these

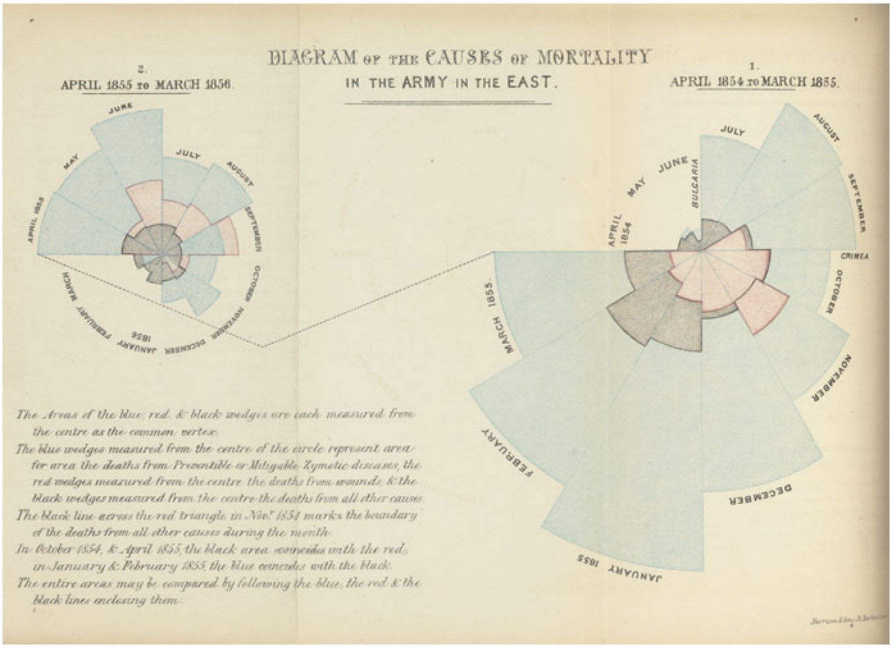

Fig. 11.3 Diagram of the Causes of Mortality in the Army in the East [40]

diagrams, it is the "radial lines . . . which shows the mortality for a particular month" and that the radii have only been joined and shaded to "impress upon the eye more clearly the rise, decline and extent of the mortality". She emphasised this by concluding that "it is not intended that the larger area should be contrasted with the smaller but simply the longer with the shorter line". It appears that Nightingale did not think this note was strictly necessary as in a letter to her sister in 1858 she complained that there was no mistake and it was only "ignorant people [who] conceive that the comparison is intended to be between the areas" [28]. However, in the same letter she conceded that those diagrams in her report that compared areas were "more mathematically correct".

The first of these "bat-wing" diagrams (Figure 11.4) is similar to Figure 11.2 in that it compares the mortality rate of the army with that in Manchester. Nightingale noted that the diagram shows how healthy the army was on arrival in the Crimea and that the rapid rise in the mortality rate during January 1855 was greater than that during the Great Plague of London in September 1665. She went on to explain that the diagram gives a pictorial representation of the great Crimean calamity during the first year of the war and then later added that this diagram means that "we have at a glance the vital statistics of the Crimean War" [29]. This shows her understanding of the power of data visualisation, something that we shall see later was not yet appreciated by many in the UK.

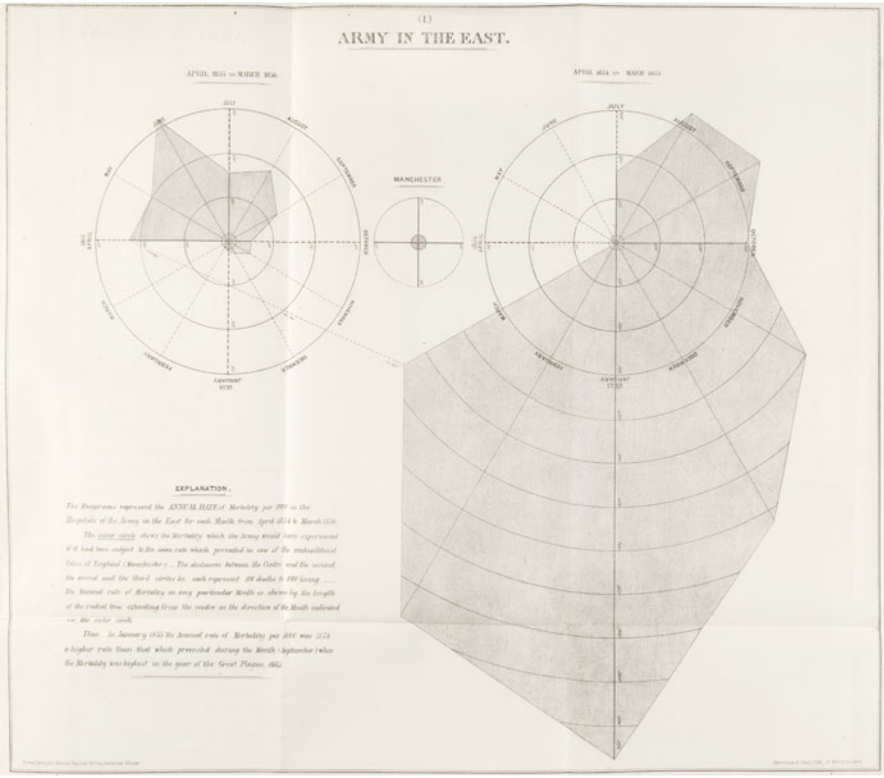

Fig. 11.4 Diagrams representing the Relative Mortality in the Hospitals in the Army in the East [40]

The second of these diagrams, Figure 11.5, is similar to Figure 11.2 in its use of colour to depict the causes of death. Nightingale explained that this diagram at a glance shows that zymotic diseases (coloured green) were “the cause of the whole catastrophe” [29]. Again, red is used for wounds and black for deaths from other causes.

Nightingale was well acquainted with the statistician William Farr and worked closely with him on several occasions. In his role as Chief Statistician in the General Register Office, he introduced statistical diagrams into the *Journal of the Royal Statistical Society* (RSS), but they were not always well received in Britain despite being used extensively in Europe. According to Cullen [4], Guerry’s early work, containing several coloured diagrams, was considered heretical. Farr himself remained suspicious of representing data in pictorial form saying at one point that statistics should be “the dryest [*sic*] of all reading” and complaining that Nightingale’s attempts were not “sufficiently dry” despite her worrying that they were too dry [8]. It is clear that she did not agree with this as she was keen to use diagrams to ensure that the data was clearly understood. There is no indication that

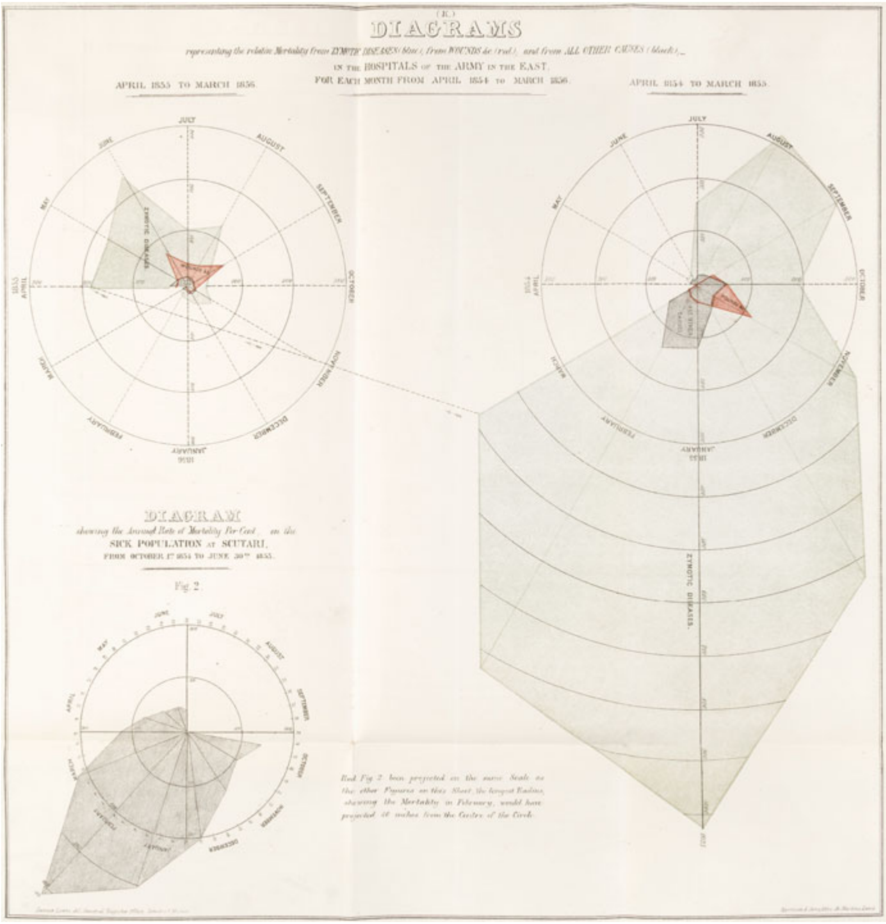

Fig. 11.5 Diagrams representing the Relative Mortality from Zymotic Diseases, Wounds, and from all other causes in the Hospitals of the Army in the East

Nightingale made any attempt to address Farr's comments. Readers interested in a more detailed commentary on other statistical diagrams of the period might like to consult the article by Magnello [14].

Nightingale also used a variety of other diagrams to portray data. Her Coxcomb contains several line graphs comparing the mortality rate of the British Army at rest with the mortality rate for the male civic population. These diagrams make it abundantly clear that there was something seriously amiss given, as Nightingale pointed out, that the soldiers entered the army in "peak physical fitness" [29] and yet when they became ill their chances of recovery were lower than for those living in densely populated areas of England.

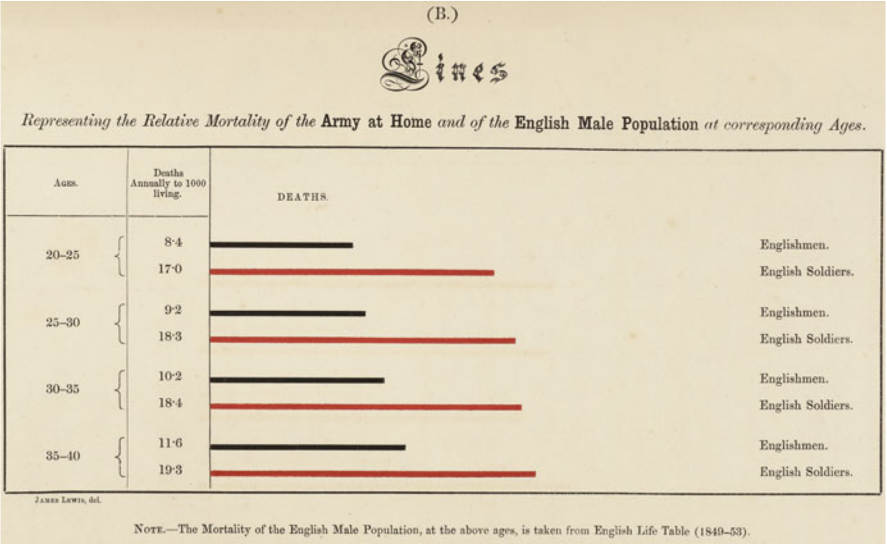

Fig. 11.6 Line graph representing the Relative Mortality of the Army at Home and of the English Male Population [40]

In Figure 11.6 the black lines denote the mortality in the general English male population and the red lines the mortality in the army on home service. Nightingale discussed this diagram at some length, echoing many of her comments from the main report. These discussions are summarised in the next section of this chapter.

Having clearly demonstrated in Figure 11.6 the differences in the mortality rates, Nightingale then constructed a variation of a bar chart to clearly show the causes of the deaths (Figure 11.7). She described these diagrams as representing the "classes of mortality from disease most prevalent in the infantry as compared with the same types of disease in civil life at the same age", noting that they "exhibit the frightful mortality continually going on in the British Army" [29]. She continued at some length to ask several pertinent questions such as "what can be the cause of all this?" before concluding that the issues were with overcrowding, poor ventilation and bad sanitation in the barracks [29]. These issues are highlighted in more detail in her main report [30] and later in this chapter.

Nightingale used the remaining two diagrams in the Coxcomb to make an even stronger political point. Firstly, in Figure 11.8 she created an unusual hexagonal representation of area which graphed the population density of a proposed army camp and compared it to known densely populated parts of London. This illustrated the Quartermaster General's plans for encamping an 850-strong battalion. Nightingale depicted the number of tents in each row of the plan and, consequently, calculated the occupied area. She noted that "it has been found that sickness and mortality bear a certain ratio to the density", with the most populated towns being the most unhealthy [29]. She then compared the density of the populations

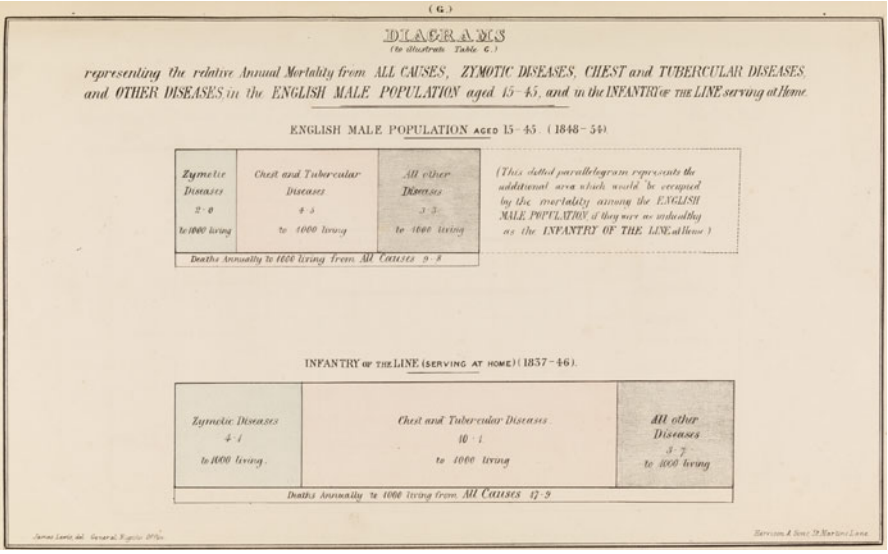

Fig. 11.7 Diagrams representing the Relative Annual Mortality from all causes, Zymotic Diseases, Chest and Tubercular Diseases and other Diseases in the English Male Population aged 15–45, and in the Infantry of the Line serving at Home [40]

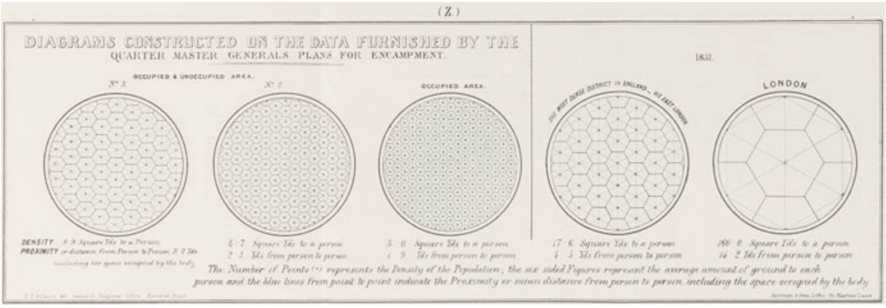

Fig. 11.8 Diagrams constructed on the Data Furnished by the Quarter Master General's Plans for Encampment [40]

in these encampments with the most densely populated part of London and the whole of London (built and unbuilt). She concluded that "these comparisons will be sufficient to show the great importance of this element of overcrowding to the health of camps" [29]. Interestingly this diagram has a whole section to itself and is labelled as Diagram Z whereas the other diagrams are labelled A-K, perhaps showing the significance that Nightingale understandably felt it deserved. After the brief description of the diagram, Nightingale provided various calculations reinforcing the issue and concluded that the "least crowded of the Quartermaster General's plans affords about a twentieth part of the area per man allotted to each

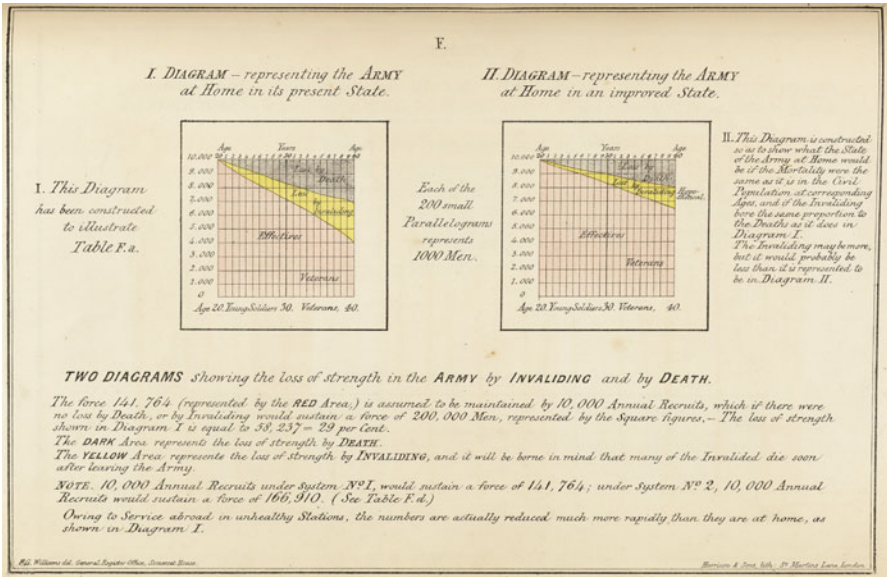

Fig. 11.9 Diagrams showing the loss of strength in the Army by Invaliding and by Death [40]

inhabitant of the metropolis; that it is about half the amount of that of the most densely peopled part of London; and that the population on the occupied area of the camp is above 50 times more crowded than the population of London" [29]. This beautifully understated punchline demonstrates what Nightingale was so adept at; clearly illuminating the fallacy of someone's decision with a simple comparative diagram or worked-through calculation.

Figure 11.9 shows a diagram where Nightingale attempted to forecast the expected health of the British Army had the soldiers been as healthy as the general British male population. This was an unfamiliar technique at the time and something that she had worked on with Farr. The black wedge represents the loss from deaths and the yellow wedge that from invaliding. She said that "by comparing the red areas of both diagrams the great loss of efficiency in the army in its present state becomes more apparent" [29]. She went on to comment that these diagrams "show the loss of life, of service and of money value entailed on the country by the neglect of sanitary measures in the army in time of peace" [29].

It is clear from the variety of graphs and diagrams and her correspondence that Nightingale was keen to ensure the optimal presentation for each set of data was used, and that the diagrams were mathematically correct [28]. Her diagrams appear to have been very ahead of their time. The accompanying commentary demonstrates how Nightingale's thinking was progressing, and how she was trying to use her diagrams to influence government policy and decision making. The use of data and quantitative methods in decision making is at the heart of what is now called Operational Research in the UK and Operations Research in the US.

11.4 The Use of Numbers

Numbers teach us whether the world is well or ill governed [7].

Nightingale used data to find out what was happening in a given situation and then presented her findings in a variety of formats, pictorial and written. She worked with Farr on many projects and, in a letter from him in 1857, he suggested that a quote from Goethe, “Numbers teach us whether the world is well or ill governed”, should be their motto [7].

During her time in the Crimea, Nightingale wrote many letters to various officials and politicians as well as to family members. In much of this correspondence, she commented on errors in mathematical and statistical calculations as well as on poor data collection and organisation. A vast number of letters are included in her report on the Crimea [30]. The following excerpts from some of these letters show Nightingale’s attention to detail, her grasp of mathematics and statistics, and her passion for seeing this portrayed correctly and relevantly to different audiences in order to change the way they thought.

In July 1855, a letter from the Commandant for the Official Information of Her Majesty’s Government reported that “Sickness has very much diminished and so has mortality” [30]. Nightingale was appalled by the erroneous figures being used to show that the mortality rate was decreasing when it was in fact increasing and pointed out that stating the number of deaths each month is meaningless without the total hospital population being quoted and the numbers given as a percentage. So, although the death toll was decreasing, she went on to show that the rate of mortality was actually increasing enormously. Nightingale described this as being “like the celebrated riddle ‘Given the height of the mast to tell the captains name’.” In other words, the Commandant had not provided sufficient information to enable the reader to ascertain the required answer. In a similar discussion, further on in the report, she cautioned that this misuse of data “gives the Secretary of State no account of his accumulated loss” [30].

Other letters illustrating Nightingale’s concern with data can be found in the Wellcome Library, London [40]. A letter to John Henry Lefroy, scientist and military reformer, in June 1856, mentioned the medical statistics of the Land Transport Corps (a branch of the army which transported military supplies), describing them as being in “a state of great confusion, so that it is hardly possible to obtain correct results” [25]. Nightingale asserted the Corps had “an extraordinary method (or no method) of keeping statistics”. She explained that one of the problems was that sometimes the natives were included in the data and sometimes not, so there was no consistency. In a letter to Lady Canning (1856) [19], she was even more unguarded in her criticism: “I could make you laugh at our classification which seems to deceive and bamboozle government as to the cause of our disease . . . I think, if you could see our real statistics, you would think that I have been moderate in my statements”.

Nightingale was concerned that one of the issues was that neither the doctors nor the government officials had the skills necessary to understand the situation and thus advise on appropriate measures to see the mortality levels decrease. In a very long letter to Lord Grey in 1857 [19], she suggested several skills that a proposed new sanitary advisor should have but then concluded, at some length, that she could not see how one person could possess all these traits. She also scoffed at the notion that the new statistical officers and sanitary officers should be the same persons: "the distinction between these two departments is an important and a practical one, as much as the distinction between food and a cookery book" [19].

Her impatience with incompetent officials and badly designed systems is particularly apparent in a letter to Sidney Herbert in August 1857 [19], where she vented her frustration while awaiting the arrival of important data. When she eventually obtained the data, she used it to work out the mortality of those individuals who had been invalided out of the army. She argued that this data must be included in the final mortality figures because "the state loses them equally whether they die or are invalided before their term of service is completed – to have kept back this data shows either utter ignorance of the importance of their bearing, or a wilful intention to keep back the truth". She then described various methods of including this data correctly and provided numerical examples of the differences this additional data made to the reported figures. In a private note to Herbert in the same missive, she confided: "The army statistics give no real idea of the mortality. There is this essential difference between the Registrar-General's and the army's medical returns. The first give the precise percentage of deaths to population within the army ages. The second give no precise percentage of deaths to army population" [19]. This criticism of army medical data and the process of data collection, as well as her suggestions of more rigorous methods, was pivotal in changing the way that British military data was gathered and recorded.

Her report on the Crimean War [30] contained a lengthy commentary on the comparative mortality rates between the general male population and the army at rest (i.e., not in battle). She explained that for the ordinary civic population aged 20–40 years and living in London the mortality rate was 8 in 1000, the rate for the Metropolitan Police was also 8 in 1000, the rate for those in English jails doubled to 16 in 1000, whereas for the British Army it was between 17.8 and 20.4 in 1000. She also discussed at length the difference in the number of days that the average worker might be sick in one year compared to a soldier in the army, finding that the soldiers take more days off sick and thus render the army inefficient [30]. She was puzzled by this as the "guards are considered the finest obtainable troops" so it would seem that they should not have such a high mortality rate. She attributed this high mortality to the conditions in the barracks. Having shocked the reader with tables of data showing that the mortality rate of the army at rest was twice that of the civilian male population, she made her point again:

> To say that the mortality in the guards is double that of civil life is to make an understatement of the truth. It is more nearly treble. For the army mortality merely shows the deaths among those staying in the service long enough to die in it. It does not show the deaths among those discharged to die elsewhere. A low mortality, therefore, may imply not a high state of health, but a high rate of invaliding ... For if every man likely to die were invalided, the army would appear immortal, for not a man in it would ever die [30].

Nightingale highlighted the overcrowding in the barracks by reporting the cubic space allotted to one man at various barracks up and down England. She commented that the so-called “new and splendid hospital” in Portsmouth (as described by the director general) allowed only half the cubic space necessary and described some of its worst features, including the lack of bathing facilities. But there was worse to come; apparently the space at Chatham, per person, was even less and there were similar horror stories at Brompton and Fort Pitt [30]. This work of Nightingale’s resulted in substantial reform of the way British barracks and military hospitals were constructed, as well as in the diet and provision of medical and nursing services for those in the army [15].

Nightingale commented at length on the validity of the statistics and calculated what she thought would be the mortality rates if those dying after having been invalided were considered. She even attempted to put a cost to the country on this premature invaliding. Having done this she provided a new method for calculating the mortality by including the invaliding and the fact that at the start those selected for service excluded the sick. With these new measures she stated that the “real annual mortality percent of the foot guards, after correction, is 26 annual deaths to 1000 living, whereas the mortality of the male population, at the same ages, is about 9 annual deaths to 1000 living” [30]. A concerning disparity!

Nightingale then listed what data needed to be collected and how it should be presented to give an accurate picture of the health of the army. She attributed the current misleading information to a misguided belief that those reporting this data thought that they might be blamed for the state of the army, instead of everyone being obliged to them for having portrayed an accurate state of affairs [30].

As well as the lengthy discussions and commentary on mortality rates, collection of data and commentary on poor numerical skills of government officials that pepper the report, she still had enough material for an entire chapter entitled “Notes on the Inaccuracy of Hospital Statistics and the Necessity of a Statistical Department”. In this chapter, Nightingale bemoaned the woeful inaccuracy of recording details of patients, something which had upset the relatives of the sick and the dead. She pointed out that by only counting the soldiers in hospital on one day per week many soldiers were missed from these returns. The nature of diseases such as cholera meant that soldiers could enter the hospital and die between counts and so not be registered as being there. Consequently she estimated that hospital records in the Crimea may have only shown one seventh of the cholera cases. She called for standardisation and explained that for the purposes of accurate comparison it was essential to have a standard measure of time and numbers under observation [30].

This chapter in her report included several excerpts of letters from Dr. Hall (a British military surgeon serving in the Crimea) to Lord Raglan (Commander-in-Chief during the early part of the conflict) which put a very positive gloss on the numbers of deaths and the mortality rate. Unsurprisingly, Nightingale also produced her own compilation of the mortality rates from various sources, showing a marked discrepancy in the data. Later she wrote, “I have carefully compared the statistics from six different official sources, and none of them agree”. She stressed that this discrepancy “shakes [one’s] confidence” in their accuracy [30]. This is something that I am sure many analysts working with data today can identify with.

She pointed out that Dr. Hall did not try to give a percentage per annum or record anywhere those soldiers suffering from zymotic diseases. She despaired over the "novel" methods of calculation used and described them as misleading. She followed this with an example that demonstrated on some occasions patients had not just been double counted, but, rather, counted more than six times! At one point Nightingale noted in frustration that the general hospitals in the Crimea had been "so deplorably mismanaged . . . that men have come to ask the question whether it would not be better to do without them altogether?" and acknowledged that general hospitals could either become "pest houses" or "be made as healthy as any other building" [30].

Many of these themes are taken up in Nightingale's later publication *Notes on Hospitals* (1863) [34]. Here Nightingale explained her view that mortality statistics gave little information on the efficiency of a hospital performance. *The Lancet* commented favourably on this publication, describing Nightingale as having "a great command over terse phrases, which she uses with telling effect, sometimes almost to the dismay of those whose souls are attuned to the sober diction and brown-suited dullness of the treatises which have appeared on such subjects up to this time" [13].

From her letters and writings, it is clear that Nightingale was keen to encourage hospital officials to understand the importance of the correct use and necessity for accurate reporting of statistics. In 1860 Nightingale sent a proposal to the ISC, held in London, advocating the uniform collection of hospital statistics, so that outcomes could be compared by hospital, region, and country. This proposal was endorsed with further measures for improving the statistics of surgical operations being validated at the ISC in Berlin in 1863 which took the analysis a step further [16]. Another substantial result of Nightingale's work was the reorganisation of army medical statistics and the setting up of a statistical branch of the Army Medical Corps [1].

As we have seen, much of Nightingale's commentary and ideas were ahead of her time. The statistician Sir David Speigelhalter said that "she clearly foresaw by 130 years, the major problems cited by clinicians . . . inadequate control for the type of patient, data manipulation and the use of a single outcome measure such as mortality" [37].

11.5 Focus on India

> I have a 'melancholy satisfaction' in recording that there is one government office worse organised than the War Office, and that is the great India House [31].

Nightingale did not concern herself with statistical and health reform only in Britain. As a result of the success of the Royal Commission on the Sanitary Condition of the Army in Britain, she was allowed to be instrumental in helping to arrange the 1859 Royal Commission that was sent to India to investigate and report on the sanitary state of the army stationed there [39]. This was an unusual accolade for a woman at that time. She took a critical interest in the statistics produced by the Indian hospitals. In a letter in 1864 to Charles Hathaway (a special sanitary commissioner for Calcutta) she wrote:

> I could not help laughing at *your* critics who 'exclude' specific diseases such as 'cholera', accidents 'proving fatal' etc. It is very convenient indeed to leave out all deaths that *ought not* to have happened, as *not having* happened. And it is certainly a new way of *preventing preventable* mortality to omit it altogether from any statement of mortality, Then they would 'exclude' 'deaths above 60.' Their principle, if logically carried out, is simply to throw out all ages and all diseases and then there would be no mortality whatever . . . [38].

Again, this is a delightfully understated and pithy comment that nonetheless makes a very powerful point.

In a letter to Lord Stanley at the Liverpool Record Office in 1865, Nightingale was still concerned about the diminution in mortality but referred to the Indians as "wading and wandering through all the discrepancies of ill-kept statistics" and acknowledged that British military statistics were in a similar mess before it had been possible to "establish reliable statistics" [38]. However, by 1869, in a letter to C. C. Plowden (a clerk in the India Office), Nightingale was much more complimentary. On returning the proofs of the annual report on the measures adopted for sanitary improvements in India, she said that despite reading them "with the utmost desire to criticize" she "cannot do so at all". She concluded by saying that she was sure Plowden would be glad that she had "so little to say on this occasion" [39].

Her involvement in analysing the data for the Royal Commission on the sanitary state of the army in India ultimately led to massive reforms in the administrative processes employed there [15]. Nightingale continued to pay close attention to issues of health and politics in India for the rest of her life and health projects in India were still the subject of many of her letters written and received during her 80s. She lobbied for Indian self-rule and continued setting up various schemes that encouraged the education of Indian women, as well as emphasised the importance of clean water, good drainage and the avoidance of overcrowding [1].

11.6 Nightingale's Goals

> The main end of statistics should . . . be to enable immediate steps to be taken to prevent the extension of disease and mortality [33].

As well as writing her report on the Crimea and investigating the mortality rate of the British Army at rest in the UK and India, Nightingale was staunchly interested in educating the working classes. She wrote several papers and publications on the topic, including *Notes on Nursing: what it is and what it is not* [32] and *Notes on Nursing for the Labouring Classes*. In the latter, there is a section on the problems for life insurance societies of using averages as "they seduce us away [first edition] from minute observation" [33]. What Nightingale was emphasising here is that it is not enough to know that 2.2–2.4% of London's population die each year in order to estimate how likely it is that a particular person will die. She explained that it is only when we drill down into the minutiae of the observations and find out which district someone resides in, and even which street and house, and then make enquiries into the conditions therein, that we can make some kind of prediction as to which families are most likely to suffer sickness and death [33].

She was a keen commentator on, and reformer of, Victorian workhouses. The Liverpool workhouse pioneered the use of trained nurses [1] as a result of a request to Nightingale from the philanthropist William Rathbone. However, according to Nightingale, the misleading use of statistics brought damage to the notion of training nurses. In a note to Charles Langton from Liverpool in 1868, she commented "I cannot help feeling that much injury has been done to the cause by putting forward figures at all as a test of nursing efficiency" [17]. She argued that hospital statistics should only represent the results of different operations and varying modes of treatment and that in Liverpool they "represent nothing, because they have never been kept with reference to any result". She concluded by saying that these figures could not show the efficiency of nursing as the trained nurses look after the more severe cases and thus their patients will inevitably have a higher mortality. This comment on the use of data to measure performance is as relevant nowadays as it was then.

In the last twenty years of her life, after many of her colleagues and collaborators, such as Sidney Herbert and Dr. Sutherland, and immediate members of her family, including her sister, had passed away, Nightingale concentrated her efforts on several projects concerned with improving the health care in rural Britain. In a letter to Frederick Verney (Nightingale's nephew by marriage) in 1890, she remarked favourably on a report from Norfolk exclaiming that the county deserved the newly instituted Victoria Cross for sanitation as they had had a surprisingly low number of deaths from diarrhoea compared to their figures from ten years before [17]. High praise indeed!

According to McDonald [18], one of the last projects that Nightingale took on towards the end of her life was the attempt to establish a Chair of Social Physics (Statistics) at Oxford in memory of Quetelet. The idea of this Chair was to provide the means of continuing the work in this area and, better still, introducing it to those who could best make use of it in society. It was first proposed in her essay on Quetelet's death in 1874, but the serious work was not carried out until 1890–91. Nightingale worked closely on this project with Benjamin Jowett—a theologian, past Vice Chancellor of Oxford and very close friend. However, despite Nightingale and Jowett's lobbying, the proposal was unfortunately turned down by the Oxford authorities owing to the subject not having a Final Honour School (final university examination) [1]. Regardless of this, in 1891, Oxford did appoint a statistician, Francis Ysidro Edgeworth, to a Chair, although this was a Chair in Political Economy rather than Statistics [10]. Edgeworth went on to receive the Royal Statistical Society's (RSS) Guy Medal in 1907 and served as the President of the RSS during 1912–14. There are now numerous Professors of Statistics in the UK, including Sir David Spiegelhalter, who was given the Winton Chair of Public Understanding of Risk and Uncertainty at the University of Cambridge in 2007, with an explicit role in communicating the subject to the general public. There can be no doubt that Nightingale's work, bringing statistics into the public domain, helped to contribute to the acceptance of statistics as a worthwhile academic subject in its own right.

11.7 Conclusion

This chapter has demonstrated that as well as being known primarily for her contribution to nursing, Nightingale played an extraordinary and pivotal role in general hospital and health management reform. Her creation of infographics to tell a data-driven story and the subsequent use of these diagrams and tabulated data to influence policy and decision makers was unusual in her time, especially for a woman of her social standing. As a result of her diagrams representing mortality data, government statistics were never the same again. Indeed, her easy-to-visualise charts were taken up subsequently in the routine publication of census and other data [2, 15].

Nightingale was instrumental in the establishment of a Royal Commission to investigate the health of the British Army in England and then played an even more pivotal role in arranging a subsequent Royal Commission to India to advise on sanitation.

Her guidelines on the collection of hospital statistics were ratified by the ISC, and this and her work comparing the mortality rates of the army at rest with the civic male population paved the way for new guidelines concerning the construction of new barracks and hospitals. These, in turn, played a major role in improving the health of the armed forces and gaining Nightingale recognition as a statistician.

In conclusion, it is obvious, just from the excerpts presented in this chapter (which are only a small fraction of those that could have been chosen), that Nightingale's analytical work was helping government and the armed forces to make better decisions. This fits within today's standard definition of Operational Research, a discipline generally regarded as having come into existence after the second world war, making her a pioneer of this branch of mathematics long before the term itself had been coined. Her use of data visualisation, cleaning, organisation and analysis also marks her out as one of the earliest data scientists.

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Chapter 12
Constance Marks and the *Educational Times*

Sloan Evans Despeaux

Abstract From 1902 to 1915, Constance Marks edited the last years of the mathematical department of the *Educational Times*, a monthly journal that in its over-sixty-year existence published more than 18,000 mathematics questions from amateurs as well as established university mathematicians. Marks carried on her editorial mission until 1918 through the monthly journal entitled *Mathematical Questions, with their Solutions in Continuation of the Mathematical Columns of "The Educational Times."* This chapter will give a short history of the *Educational Times*, and it will explore Marks' editorial career and her unusual position as a female mathematician and editor of a mathematics journal at the beginning of the twentieth century.

Keywords Constance Marks • *Educational Times* • *Mathematical Questions* • Mathematics editor

12.1 Introduction

"A Lady Editor" announced the title of a short article appearing in the Welsh newspaper, the *Morning Leader,* on 23 October, 1901 (see Fig. 12.1). Below the picture of a determined-looking woman in a cap and gown, the article related:

> Miss Constance I. Marks, who has been appointed editor of the Mathematical Section of the "Educational Times," is a daughter of Mr. B.S. Marks, the artist. She was born in Cardiff, but has been educated entirely in London. When a very young child, says the "Jewish World," Miss Marks showed aptitude for intense application, and as she grew older her favorite study was mathematics. Since taking her B.A. degree a few years ago at the London University she has been a diligent and devoted student of the Higher Mathematics, both pure and applied [3].

S.E. Despeaux (✉)
Western Carolina University, Cullowhee, NC, USA
e-mail: despeaux@wcu.edu

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A LADY EDITOR.

Miss Constance I. Marks, who has been appointed editor of the Mathematical Section of the "Educational Times," is a daughter of Mr. B. S. Marks, the artist. She was born in Cardiff, but has been educated entirely in London.

When a very young child, says the "Jewish World," Miss Marks showed aptitude for intense application, and as she grew older her favorite study was mathematics. Since taking her B.A. degree a few years ago at the London University she has been a diligent and devoted student of the Higher Mathematics, both pure and applied.

Fig. 12.1 The October 23, 1901 issue of the *Morning Leader* announced Constance Marks as the new editor of the Mathematical Department of the *Educational Times* [3]. ©British Library Board (shelfmark MFM.M44648 [1901])

This chapter aims to explore Marks' path from an intense child to mathematics graduate to journal editor and beyond. This path wound through the limited possibilities for a woman who wanted to pursue mathematics as a career at the turn of the twentieth century. We will also explore the journal to which Marks devoted almost two decades of her working life, the *Educational Times*. By the time Marks took her editorial role there, the Mathematical Section of the *Educational Times* was part of a British mathematical journalistic genre that was almost two centuries old. This genre, centered around posing and answering mathematical questions, enjoyed an active and devoted readership that consistently defied the pressures of stratification emerging as mathematics began to become professionalized. The genre's relationship with female contributors can best be described as "on and off"; however, it was a woman who led the leading British questions and answers journal into the twentieth century.

12.1.1 Women in Question and Answer Journals

The first commercial journals in Britain to contain mathematics, and in particular, mathematics by women, were almanacs. One of the first British almanacs to contain mathematics was the *Ladies Diary*, initially established in 1704 as an almanac with articles for homemakers. However, by 1708, it had replaced many of its domestic features with mathematical ones in response to some of its readers, who had, of their own accord, submitted mathematical questions to the editor [9, 52]. The new formula was successful, and the *Ladies Diary* survived until 1840 and during its lifetime published 1778 mathematical questions.

The role of women in the *Ladies Diary* changed over the years. Although it sought to set itself apart from the other almanacs by appealing to the "fairer sex," women did not form the majority of the contributors. In her investigation of gender in the *Ladies Diary*, Shelley Costa found that between 2 and 12 acknowledged mathematical contributions to the *Diary* for selected years between 1711 and 1724 came from women (this comes to 11.4% of all acknowledged contributions for these years). However, the actual number of women corresponding with the editor was many times this number. Costa described a process beginning in the 1720s that changed the *Diary* "from a forum where women's 'geometrical, algebraical, astronomical and philosophical' skills were displayed and praised to one nominally dedicated to women and to mathematics, but in which polite banter had been displaced by an increasingly skill-oriented, even confrontational, discourse" [9, p. 70]. Questions, initially posed in rhyming verse, were replaced by those set in prose, figures, and equations. "With these changes, contributing mathematically to the *Ladies Diary* lost the surface characteristic of 'polite accomplishment' that it had formerly shared with acceptably feminine activities such as music, dancing, horseback riding, and poetry." As a result of this change, "women dropped out of its mathematical dialogue for more than twenty years, resurfacing [by mid-century] only in very reduced numbers and in a much more competitive context" [9, pp. 71–72].[1]

The format of mathematical questions and answers in commercial journals was immensely popular and was copied many times throughout Britain during the eighteenth and much of the nineteenth centuries.[2] The journal that would take this format into the next century, with a twentieth-century woman at the mathematical helm, was the *Educational Times*.

12.1.2 The Educational Times: An Active Venue for Mathematics

The *Educational Times* (*ET*) was a journal of the College of Preceptors, an organization that was founded in 1846 with the aim of certifying teachers through examination and soon extended its reach to include external examinations for secondary students. In line with the goals of the College, the focus of the *ET* was

[1] In the midst of these changes, the *Ladies Diary* was briefly edited by a woman. Elizabeth Beighton, wife of longtime editor Henry Beighton, co-edited the *Diary* in 1744 after her husband's unexpected death [5, p. 18].

[2] For a table containing a sample of 34 of these journals, dates of existence, formats, and features, see [15, pp. 55–59].

pedagogical; the journal included mathematical teaching methods and past Preceptor's examination questions along with sample answers. In 1849, two years after the journal's foundation, the "Mathematical Questions and Solutions" department was established in response to the rapid influx of mathematical questions into the *ET*. From the beginning of their tenure as editors of the mathematical questions section until 1862, College of Preceptors members Richard Wilson and James Wharton wanted the mathematical solutions published to demonstrate solid methods to assist both teachers and students. They often published several different solutions to the same question so that the possible variety of approaches could be demonstrated [12, p. 141].

In its early years, the *ET* published many mathematical contributions made by the students and their mathematical masters at the Dissenters' College in Taunton, in southwestern England. A notable Dissenters' College student contributor was William John Clarke Miller. He continued contributing after graduating and gaining employments as a teacher at several schools. He could not study at Cambridge due to his family's religious convictions. The mathematical problems of the *ET*, however, provided a pathway for him to develop his mathematical talents [12, pp. 129, 139]. Miller became editor of the mathematical department of the *ET* in 1862 after Wharton's death; he held the editorship until 1897 [12, pp. 127–128].

As the new editor, Miller "expressed his long-held desire to see original problems posed and solved in the *ET*. He also made his target audience very clear—distinguished mathematicians. His aims were certainly not purely didactic" [12, p. 127]. Besides these changes in the character of the mathematical department,[3] Miller wanted to address the section's perennial lack of space by publishing a separate reprint of the section. He asked mathematicians for support by subscribing and contributing to his new endeavor. The reprint, which began in 1864, was called *Mathematical Questions with their Solutions Taken from the "Educational Times"* (*MQ*). This new publication appeared annually and contained all of the mathematical material from the *ET* as well as new solutions and short mathematical articles.

In the space of just one year, the British mathematicians, Arthur Cayley, James Joseph Sylvester, Augustus De Morgan, William Kingdon Clifford, Thomas Archer Hirst, and Isaac Todhunter, and foreign mathematicians Pierre Marie Eugène Prouhet and Luigi Cremona had all made contributions to the journal [12, pp. 115, 316, 322, 325]. However, the presence of these mathematical stars did not diminish participation by provincial school masters, country parsons, and others involved in mathematics recreationally. At a time when mathematics was beginning the slow process of professionalization (the London Mathematical Society was founded in 1865), the *ET* and *MQ* resisted the concomitant process of stratification. In fact, the doors of the journals opened widely enough to include participation by women, especially in the last two decades of the nineteenth century.

[3]During the 1850s, the mathematical department usually occupied a page and a half per each 24-page issue [34, p. 70].

12.1.3 Women in the ET, 1850–1899

In his exhaustive research on the contributors to the *ET* and the *MQ*, Jim Tattersall has identified 42 female contributors over the journals' lifetimes. This number surely gives an underestimate of female participation because of the use of initials only for first names, or the use of pseudonyms.[4] This practice was certainly not limited to the *ET* and the *MQ*:

> Anonymous publication has been ... extremely significant for women in journalism particularly in the central decades of the nineteenth century, operating complexly both as an aid and a hindrance. Unsigned articles allowed women to enter debates of the day but also to enter the industry itself, giving access, protection, and conferring a degree of authority. Anonymity, however, also meant that women contributors to periodicals often received no 'credit' for their work [17].

Women first definitively appeared during the period of 1850–1853, when five women made 14 contributions. It would be almost twenty years later before signed contributions from women reappeared. In the period of 1871–1916, around 1.7 percent of the problems and 6.2 percent of the solutions were published under women's names. Ten women were active in the 1870s, including, most notably, Christine Ladd, who was the most prolific of all women contributors with 53 problems and 82 solutions. Sylvester, another active *ET* contributor, noticed the analytical prowess of Ladd's *ET* solutions and later supervised Ladd's graduate mathematics studies at the Johns Hopkins University [33, pp. 154–156]. The 1880s and 1890s were the most active decades for female contributors to the *ET* and *MQ* with 30 such contributors. One of these was Sarah Hertha Ayrton (née Marks),[5] who posed 22 problems and solved 95 over a period of almost twenty years. Educated at Girton College, Cambridge, Ayrton later became a leading electrical engineer and suffragist [28]. Several of the female contributors during the 1880s and 1890s were trained at the colleges of Girton or Newnham, established in 1869 and 1871 respectively as the first Cambridge colleges for women [33, pp. 157–161].

Constance Marks made her first contribution (the solution to a problem) to the ET in 1899 in volume 71. The mathematical editor at that time was Daniel Biddle, a physician and Fellow of the Royal Statistical Society. Biddle had taken over the editorship from Miller in 1897 and would pass it on to Marks in 1901. While the details of this editorial transition are unclear, we know enough about Marks' mathematical training and career trajectory to see why she was an ideal choice to lead the *ET* and *MQ* into the twentieth century.

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[4] About 650 problems and 300 solutions were attributed to pseudonyms. This practice rapidly declined after 1870 [33].

[5] It does not seem that Sarah was related to Constance Marks [28].

12.2 Constance Marks

12.2.1 Family and Mathematical Training

Constance Isabelle Marks was born 15 December 1860, the second of six children, to Barnett Samuel Marks and Zipporah Marks in Cardiff, Wales. B.S. Marks was a notable portraitist and moved his family in 1867 to London, where he painted portraits for such notables as the Prince of Wales (later King Edward VII) and was an active member of the Jewish community in London [1, 21].

Constance earned a BA from the University of London in 1888 [35]. Besides the University of London, by the turn of the twentieth century in Britain, there were a number of options for women to pursue a Bachelor's degree in mathematics (however, Cambridge and Oxford only allowed women to take examinations and did not actually confer degrees to them). Post-graduate opportunities for women—in the form of research opportunities or employment—were very limited. Teaching in girls' high schools was a popular employment option [23, pp. 144–145, 153]. Marks, however, chose to tutor privately: in an 1889 issue of *The Academy. A Weekly Review of Literature, Science, and Art,* she advertised that she "gives LESSONS in PURE MATHEMATICS, CLASSICS, FRENCH, and ENGLISH, and COACHES for Public Examinations" [4].

During this period, marriage often signaled the end of a woman's academic career. However, Constance, as well as her three sisters, chose careers over matrimony. According to the 1911 Census, the then 50-year-old Constance was still living with her father B.S. Marks (widowed and aged 82) along with her sisters Gertrude (aged 48, "Maternity nurse certified"), Florence Helena (aged 46, "Music teacher"), Anne (aged 45, "Artist (Painter)"), and youngest brother Percy (aged 43, "Architect and Surveyor") [2]. Besides teaching music, Florence Helena, who never married, published several songs, painted portraits, and exhibited at the Royal Academy [13, 16, 21]. Anne also never married, and showed her art at the Royal Academy as well as with her father at his studio at Addison Hall in Kensington [14, 16, 18]. Besides her father Barnett Samuel Marks, her siblings Anne, Florence Helena, Gertrude (also never married), and Percy all appeared in the "Who's Who in British Jewry" section of the 1901 *Jewish Year Book* [18]. (Constance appeared in the 1905 *Year Book* [19].) Thus, Constance, a woman with a taste, talent, and training for mathematics, found herself as part of a family that obviously did not see a need for its daughters to be married. She had the freedom to pursue mathematical opportunities in London, which led her to the *ET* and *MQ*.

12.2.2 Appointment as Editor

Marks' 1901 appointment as the editor of the mathematical section of *ET* was covered in several journals and newspapers. These notices give us a few more details into Marks' mathematical life and underscore the impact that her appointment made in publication circles. The journal *Womanhood: The Magazine of Woman's Progress and Interests—Political, Legal, Social, and Intellectual—and of Health and Beauty Culture* announced Marks' appointment and noted that "she has been a student almost from her infancy, and, since taking her B.A. degree some years ago at London University, has devoted herself to the higher mathematics. She is an examiner on mathematical subjects" [6]. The Cardiff-based daily newspaper, *Evening Express*, announced Marks' appointment on October 23, 1901 [20]. The next day's issue of the same newspaper contained the following commentary:

> Lady editors are not very generally met with, for to our dismay we have found that some men have had the effrontery to permit the public to assume that the office of editors of some of the newer magazines that have come so much into favour among ladies is fulfilled by men [8].

The author cited the Cardiff-born Marks as a counterexample [8]. Notice of Marks' appointment also appeared the next day in the Welsh weekly newspaper *The Cambrian,* which reported that yet another newspaper, *The Morning Leader,* had just "reproduced a photograph of the new lady editor, attired in the academic mortarboard and gown" (the piece quoted and image shown at the beginning of this chapter) [30]. How unusual was the concept of "lady editor" at this time? One way to approach this question is to look at the English census, which listed 15 women as "author, editor, journalist" in 1841 and fifty years later listed 660 [17, p. 4]. For her part, Marks listed herself as occupied with "General mathematical work" and as a "Private Coach" in the 1911 census [2].

12.2.3 Life as an Editor

Despite the notice Marks was given in the periodical press, the *ET* passed the editorial torch without fanfare. However, Marks, unlike her predecessor, was given a clear job title. While readers on August 1, 1900 were directed that "all Mathematical communications should be sent to D.Biddle, Esq., Charlton Lodge, Kingston-on-Thames," a year later, readers were told to send these communications "to the Mathematical Editor, Miss Constance I. Marks, B.A., 10 Matheson Rd., West Kensington, W" [31]. With Marks' arrival, the *MQ* began a new series and restarted its volume numbering. The new editor's presence in the journals was constant yet subdued. During her tenure as editor, Marks wrote only twenty "Editorial Notes," "Remarks," "Discussions," or "Notes" [32]. In these notes, she educated her correspondents ("It is at once evident . . . Now with a little consideration . . . it follows that . . . " [26]); refereed disputes ("The two solutions furnished to this Question . . . are in perfect agreement" [24] and ". . . we gave an interesting theorem connected with recurring decimals and from the pen of Mr. W.D. Ross. The theorem, we find, must be added to the list of those which from time to time have been discovered independently by more than one mathematician" [25]); and managed her workload ("The Editor reminds contributors that manuscripts submitted with a view to possible publication are not, in general, acknowledged otherwise than by such publication (if selected) ... The direct criticism of manuscripts offered for the mathematical columns ... does not, in general, lie within the province of the Editor" [27]). Her innovations as editor included adding "subject and author indices to *MQ* and short articles and poetry to each issue of *ET*" [33, pp. 153–154].

Marks was elected a Member of the London Mathematical Society (LMS) on 11 June 1903 [29]. She joined a group of thirteen female members out of the Society's 361 ordinary members [23, p. 156]. In her study of the 18 women who formed the totality of the female LMS membership up to 1914, Jones records that twelve of these women published 48 mathematical papers in English language mathematics journals (not including the *ET* or *MQ*) up to 1914 [23, pp. 160–161]. If we look at this group's participation in the *ET* and *MQ*, we find that eight of them (six of the 12 authors that Jones flags plus two more) posed 75 questions and solved 207 (over 30% and 36% of the total posed and solved by women, respectively). For her part, Marks solved 50 questions and posed nine [32]. Interestingly, during Marks' tenure as editor, only four women (including herself) made contributions to the *ET* or *MQ*. Of these, one is completely unknown (Edith J.D. Morrison), and another, Alice Gordon, wrote from Barnwood House in Gloucester, "a private hospital for the insane ... It is not clear whether Gordon was a patient or a member of the staff" [33, p. 191]. Only Frances Evelyn Cave-Browne-Cave, a Lecturer in mathematics at Girton College and LMS member, seems to have possibly run in similar mathematical circles as Marks. Thus, while Marks' appointment as a female mathematical editor surely broke some gender barriers and gained notice in the press, it does not seem to have inspired many women to contribute to her journals.

By 1915, Marks had overseen the submission of over three thousand mathematical questions. In that year, the *ET* decided to drop its mathematical problems section. The *MQ* survived under Marks' editorship for three more years. Marks began a new series in which subscribers were sent a short list of questions monthly. These lists included new questions (numbers 18,139 to 18,702) as well as "Old Questions Set but not Solved in 'The Educational Times'." The questions and solutions appeared in the volumes entitled *Mathematical Questions with their Solutions, in Continuation of the Mathematical Columns of 'The Educational Times',* which appeared in semiannual volumes [33, p. 152]. The last volume of this new series, Volume VI, was published in July of 1918, and the last monthly installment of questions was sent in December of that year, with no indication that question number 18,769 would be the last question posed in this remarkable specimen of mathematical journalism and communication that spanned almost 70 years.[6]

[6]It would be very difficult to give enough mathematical examples from the *ET* and *MQ* to provide a representative sample of the range and types of questions one could find there for over 70 years. Therefore, the author encourages readers to explore the *MQ* through copies readily available online. See https://catalog.hathitrust.org/api/volumes/oclc/47280158.html and https://catalog.hathitrust.org/Record/000552164. Along with Jim Tattersall and her computer scientist colleague Mark Holliday, the author is in the process of putting together an online database with

12.2.4 After the ET

After her tenure as editor of the *ET* and the *MQ*, Marks stayed active in mathematics and editing. In particular, she had a fruitful collaboration with one of her former *ET* contributors, Lt.-Col. Allan Joseph Champneys Cunningham. Born in Delhi in 1842, Cunningham was educated at King's College London. After a military career spent mainly in India, Cunningham retired from the Army in 1891, and devoted the rest of his life to mathematics, specifically number theory, and especially on factoring numbers of the form $a^n \pm b^n$. He served on the council of the London Mathematical Society from 1892 to 1902 and was vice-president in 1898 [7, 36]. He was a regular contributor to the *ET*. He made his début in the journal in 1898, the year before Marks' first appearance there, and he continued contributing until the *MQ*'s demise in 1918. In those twenty years, he posed 209 problems and solved 426 [32].

As early as 1912, Cunningham was announcing in the *ET* that his work, *Binomial Factorizations. Giving Extensive Congruence-Tables and Factorisation-Tables* was "now in press." This massive work ("the outcome of the author's labours of the past thirty years") was "greatly delayed by the War and by its aftermath," and the first volume only appeared in 1923 [10]. Cunningham employed several assistants to carry out most of the computation of the tables. Of the nine assistants listed in the first five volumes (printed in 1923 and 1924), only two were male. The job of human "computer" was another career option for female mathematics graduates in Britain. A computer would complete complex calculations and statistical analyses in a research lab such as Cunningham's or (for statistics) Karl Pearson's, an observatory, or an insurance concern [23, pp. 154–155]. Constance Marks' name first appeared in Cunningham's *Binomial Factorizations* in Volume III, when Cunningham referred to her as the "author's assistant" who had extended his congruence tables "to much higher limits" than had been previously done by his staff [11, p. xix]. By 1925, seven volumes of *Binomial Factorizations* had been published. The remaining two volumes of the series were edited by Marks and published in 1927 and 1929 (Cunningham died in 1928 at the age of 86). Thus, besides teaching, coaching, and editing, Marks pursued yet another avenue of possible mathematical employment for women.

12.3 Conclusion

At a time when most women with an interest and training in mathematics followed the career path of teacher at a girls' school, Constance Marks found her own path as private tutor, editor, and computer. Under her stewardship, the *Educational Times* published over 3500 questions. Marks kept a communication venue alive that

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which one can search by author through the mathematical content of the *ET* and *MQ*. As this is still a work in progress, please email the author with any questions or interest.

enabled mathematicians of different educational backgrounds and occupations to actively discuss mathematical questions that varied from the purely recreational to those which J.J. Sylvester maintained "really contain the germs of theories" [22]. By editing Cunningham's *Binomial Factorizations*, she continued to do valuable mathematical work well into her late 60s.[7] Thus the "aptitude for intense application" that Constance Marks showed as a child seems to have propelled her to carve out of a field with narrow opportunities for women a varied and rewarding mathematical career.

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Chapter 13
The Two Mathematical Careers of Emmy Noether

Colin McLarty

Abstract The received view of Emmy Noether as the champion of David Hilbert's new style of algebra is not false (as you can see from the fact that Hermann Weyl urged this view). But it seriously understates Noether's mathematical ambition and her influence on young mathematicians around her and on all of mathematics since. In fact Noether was an internationally recognized mathematician by age 30, teaching unofficially in Erlangen, before she took up the new algebra or began any of her work that is remembered today. That first career, though it used quite old-fashioned mathematics even by the standards of Erlangen, gave her insights she carried on throughout her very different, distinctively 20th century career in Göttingen and Bryn Mawr.

Keywords Emmy Noether • Invariant theory • Mathematical physics • Conservation laws • Algebra • Commutative algebra • Group representations

13.1 Her Life in Brief

Several people who knew Emmy Noether (1882–1935) in her infancy supposed she could become a mathematical heroine, and they lived to see it. Her father Max was a mathematics professor. Her future doctoral supervisor, Paul Gordan, was a family friend. Felix Klein, who had unparalleled influence over German mathematics, and championed University education for women [70, p. 87], was close to Gordan and friendly with Max Noether. Her parents and these friends lived to see her an internationally recognized mathematician. But Gordan died in 1912, and her mother in 1915, before Emmy did any of the work people know her for today.

C. McLarty (✉)
Case Western Reserve University, Cleveland, OH, USA
e-mail: colin.mclarty@case.edu

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By age 30, in 1912, she had published her dissertation in Crelle's journal [46]. She spoke at conferences and was elected to the *Circolo Matematico di Palermo* (Mathematical Circle of Palermo) in Italy in 1908 and to the *Deutsche Mathematiker-Vereinigung (DMV)* (Association of German Mathematicians) in 1909. She unofficially supervised a doctoral dissertation.

Whether Noether wished for a faculty title and a salary, we do not know. Fortunately for mathematics the family was very well off. Noether probably saw no practical way and no urgent need for her position to change - and if it had not changed she would still figure among the pioneering women in mathematics.

In fact everything changed except the salary. Bryn Mawr was trying to get a salary for her when she died.

Her 1913 paper, *Fields of rational functions* [47], announced a project using Gordan's perspective to simplify and extend aspects of David Hilbert's algebra. Contrary to Hermann Weyl's claim that she abandoned Gordan's views for Hilbert's, Noether's published statements and the work itself show she continued drawing on Gordan. As she herself said, her greatest inspirations were Sophus Lie and Richard Dedekind, though she never met either of them. At some point Klein and Hilbert began arranging to bring her to Göttingen.

The Great War began. In four years, with 2 million German soldiers dead fighting outside the Reich, at home Germany lost over a half million civilians to famine. After the War the bloody German Revolution of 1918–1919 ended with the founding of the Weimar Republic.

In 1915 Noether went to Göttingen. She published the key steps in her announced project and then turned briefly to the famous Noether Conservation Theorems [51]. These became a landmark in the foundations of General Relativity and the working methods of Quantum Mechanics yet they were something of a sideline to her. At the time she died these theorems were less famous than they are now and Paul Alexandroff said:

> Emmy Noether was herself partly responsible for her early work being remembered less frequently than would be natural. For with all the fervor of her nature, she was herself ready to forget what had been done in the first years of her mathematical activity, considering these results as standing apart from her true mathematical path—the creation of a general abstract algebra. [5, p. 101]

The family money was disappearing. She lived on the edge of poverty [29, pp. 44ff.]. In 1919 she joined the Independent Social Democratic Party (USPD). Many people regarded the USPD as covert agents of Russian Bolshevism and this was the position of the ruling Social Democrats (SPD). The USPD adopted Bolshevik slogans and called for a dictatorship of the proletariat [40]. She travelled several times to Moscow and was widely known to her colleagues as pro-Soviet.

In the 1920s she formed a grander project to algebraize all of pure mathematics by reorganizing it around her *Homomorphism and Isomorphism Theorems* replacing equations by maps between structures.[1] Alexandroff wrote of Noether's 1923 visit to Moscow:

> The basic features of the Noether school struck us right away: the intellectual enthusiasm of its leader, which was transmitted to all of her students, her deep conviction in the importance and mathematical fertility of her ideas (a conviction which far from everyone shared at that time, even in Göttingen), and the extraordinary simplicity and warmth of the relations between the head of the school and her pupils.

Noether absolutely did not mean this fertility would be confined to factorization theorems for rings such as she had actually proved by that time. No one in Göttingen doubted her ideas had been good for that!

So she created modern commutative algebra and passionately urged it as a basis for algebraic topology and algebraic geometry and number theory. Koreuber [29] documents how conscious she and her students were of founding a coherent movement. Alexandroff and Hopf in their textbook, *Topology* [6], and van der Waerden in his textbook, *Modern Algebra* [80], and in his articles on algebraic geometry beginning with [79], made commutative algebra basic to those subjects, as it still is today. Alexandroff and Hopf [6, p. ix] specify that this conquest of topology required "all the energy and the temperament of Emmy Noether." Her work with Brauer, Hasse, and others made her techniques basic to number theory, and specifically to class field theory [66], as they still are today. She became a giant of 20th century mathematics—and of mathematics still today.

Weyl knew her ambition and saw it becoming reality. He spoke at a 1931 conference on topology and abstract algebra as competing styles of mathematical understanding, and later repeated the remarks in his Eulogy to Emmy Noether at Bryn Mawr. Despite his deep appreciation for what she achieved, he felt her algebraic style was taking over and damaging mathematics as a whole. He very specifically warned that not only her research line would dry up, but an entire generation would be lost:

> Before you can generalize, formalize and axiomatize, there must be a mathematical substance. I think that the mathematical substance in the formalizing of which we have trained ourselves during the last decades, becomes gradually exhausted. And so I foresee that the generation now rising will have a hard time in mathematics. [83, pp. 140f.]

Her 1932 plenary address to the International Congress of Mathematicians in Zurich unified her latest number theory with problems she addressed back in the 1910s. She was then expelled from teaching at Göttingen by the Nazis. Weyl and others got her a position at Bryn Mawr College—near to, but not at, Princeton

[1] Noether wrote that she meant to restructure Galois theory [50], basic abstract algebra and algebraic topology [55], invariants of groups [56], algebraic number theory and the theory of complex algebraic functions [57], group representation theory [58], and class field theory [59, 60], all by resting them on homomorphism and isomorphism theorems. Her students say she extended exactly this to point set topology [5, p. 108] and algebraic geometry [81, p. 173].

where Weyl was and many felt she belonged. Anna Johnson Pell Wheeler (Ph.D. Chicago 1910, after study with Hilbert in Göttingen) was head of Mathematics at Bryn Mawr. She made very sure everyone understood who Emmy Noether was. Writing from Princeton, Albert Einstein said Noether's colleagues and students at Bryn Mawr "made her last years the happiest and perhaps the most fruitful of her entire career" [15].

She died at 53, with her mathematical powers still growing. She doubly refuted the story that mathematics is a young man's game.

13.1.1 How Others Saw Her

Weyl probably relied on Emmy's admiring younger brother Fritz for information about her life in Erlangen:

> There was nothing rebellious in her nature; she was willing to accept conditions as they were. [83, p. 122]

Paul Alexandroff was a close friend and an influential topologist:

> Her great sense of humor, which made social gatherings and personal contacts with her so pleasant, enabled her to counter the injustices and absurdities that beset her academic career easily and without anger. In such circumstances, instead of being offended, she would simply laugh. But she was very offended indeed, and protested sharply when even the smallest injustice was directed at one of her students. ([5, p. 110], compare the letters [75])

Noether's student Olga Taussky-Todd reported:

> Not everybody liked her, and not everybody trusted that her achievements were what they were later accepted to be. She irritated people by bragging about them. ([74, p. 84], compare Tauissky-Todd's humorous poem on Noether [73])

A Nazi Ministry of Education representative reported in 1933:

> From the revolution of 1918 to today Miss Noether has had a Marxist stand. And while I think it possible that her political position is more theoretical than committed and practical, I am also convinced she has such strong sympathy for the Marxist world view and politics that she can not be expected to enter unreservedly into the national state. [76, p. 206]

Weyl, Alexandroff, and Taussky-Todd all deeply admired Noether as a person and as a mathematician. The Ministry finally found her "non-aryan ancestry" sufficient to bar her from teaching [76, p. 210].

13.2 Growing Up to a Career in Erlangen

Amalie Emmy Noether was born 23 March 1882 in Erlangen to Max and Amalia (née Kaufmann) Noether. She had no nickname but two given names on her birth certificate, Amalie Emmy. The next year her brother Alfred was born (he had health problems but got a doctorate in Chemistry at Erlangen); and the year after came brother Fritz, another mathematician. A fourth child, Gustav Robert, born in 1889, suffered chronic illness [12, 24, 76].

Friedrich Nietzsche may have met her. He enjoyed talking with Max Noether at the Hotel Alpenrose in Sils Maria, Switzerland in 1887. But Nietzsche wrote to his mother that the dining room "is hot, too crowded (ca. 100 people, many children), noisy" [64, p. 42]. Five-year-old Emmy may have added to the noise, or shared his chagrin at it.

She was first educated as a girl's teacher of French and English. This could reflect a disinclination to marry, since married women could not teach [29, p. 12]. But she had little choice if she ever needed to work. The Prussian *Beamtinnenzölibat* legally barred married women from essentially any job acceptable in middle class life [1, p. 26]. Immediately after qualifying as a language teacher Noether began university study.

She became one of two women students at Erlangen, with 984 men. Women could only audit and then only with permission from each professor. Tollmien [76] describes the long history of resistance to women's education in Germany in Noether's time.

Noether spent the winter term of 1903–1904 at the University of Göttingen attending lectures by figures famous to her including Hilbert and Klein. It left little discernible trace on her later work. Her publications suggest that into the mid-1920s she preferred to learn by extensive reading of the leading journals and standard references, which would make sense in Erlangen with just two mathematics professors. Later, in 1920s Göttingen, interaction with her growing circle of students and colleagues, and her own accumulating achievements, became more important sources.

When she returned to Erlangen, the University was accepting women as full fledged students. She chose mathematics and finished her dissertation in 1908 with Gordan. She went to the 1908 International Congress of Mathematicians in Rome which was probably one reason she was elected to the Circolo Matematico de Palermo. She befriended Luitzen Brouwer at the 1912 *Deutsche Mathematiker-Vereinigung* meeting in Karlsruhe [77, p. 959]. In Erlangen she co-supervised Hans Falckenberg's dissertation 1911 under her father's name.

13.2.1 Noether's 19th Century Mathematics

Historians say the *long Nineteenth Century* ended in 1914 as the Great War closed an era. This fits Erlangen well. Visitors from northern Germany found the town old-fashioned. Emmy Noether's 1908 dissertation [46] was old-fashioned even compared to Gordan's work of the 1890s. Very little of it is comprehensible today despite considerable efforts described below. It makes no sense at all outside the context of Gordan's work. Yet it won her international recognition in mathematics.

Further, Section 13.5.1 will argue the greatest misunderstanding of Noether today is Weyl's claim that her mature algebra marked a movement away from Gordan and towards Hilbert. To understand either Noether's Erlangen career or her work in Göttingen, we must see her work with Gordan.

Gordan was known at the time for his classical invariant theory, a highly technical subject which is all but forgotten today. In his hands it was a thoroughly calculational subject actually calculating *systems of invariants* for certain polynomials. For example, the discriminant $b^2 - 4ac$ is an invariant of the quadratic polynomial $aX^2 + bX + c$, and, in effect, its only invariant. Today Gordan is remembered only for rejecting Hilbert's abstract algebraic Basis Theorem by saying "This is not mathematics, it is theology!" According to legend, he objected because Hilbert's theorem did not construct explicit answers to problems. In fact, he helped Hilbert find that proof. The story of rejecting it arose after Gordan died.[2]

Gordan always knew Hilbert's proof could yield explicit constructions [33]. He published three papers from 1893 to 1900 showing this:

> with the explicit remark that I would not have succeeded at finding [this] had not Hilbert shown the value for invariant theory of certain ideas which Dedekind, Kronecker, and Weber developed for use in other parts of algebra. [19, pp. 132–33]

Noether agreed with Gordan about this, in print, years later when she was in Göttingen [53, p. 140n].

For some reason, though, Noether did not pursue that. In 1907 she began her dissertation on a vast calculation Gordan had broached and abandoned in 1880, using his *symbolic method* to find a *complete system of invariants* for the *ternary biquadratic form*. She did not finish it either. Crelle's journal published over 60 pages of her calculations. She made two general claims:

1. Each step produces invariants of the ternary biquadratic form.
2. Every invariant is a combination of invariants reached this way.

Claim 1 is clear from the calculations. To show she would eventually finish, she mentions Hilbert's finiteness theorem without citation [46, p. 24]. It is hard to see why she believes Claim 2. Why should this method reach a complete system? Noether calculates at great length, breaks off with a certain "relatively complete system" of 331 invariants [46, p. 89], and offers no estimate of how long it would take to find a complete system. This is too typical of 19th century mathematics.

Gordan's symbolic method introduces new symbols and calculating rules. It speeds calculations while, according to Gordan, it is "a purely symbolic process. No meaning can be assigned to it" [18, vol. 2, p. 10]. Only the resulting non-symbolic invariants, after the symbols are calculated away, have meaning [42, pp. 109–13]. Gordan's proofs were, and remain, obscure.

[2]For a sketch of classical invariant theory and discussion of Gordan's remark, see [42]. One student of Hilbert in the 1890s later took the quote to mean the proof was "a ray of light from a higher world penetrating our earthly darkness" [31, p. 25]. Gordan was known for a "keen sense of humor," though, not piety [83, p. 117].

Gian-Carlo Rota and Joseph Kung spent years studying the method. They clarify Gordan's calculations beautifully in his original notation. "A similar salvage operation could not, unfortunately, be carried out on the proofs" [34, p. 28].

This is no recent problem. At the peak of Gordan's career Klein called one of Gordan's results: "no doubt a splendid piece of work; it is only to be deplored that Gordan here, as elsewhere, has disdained to give his leading ideas apart from the complicated array of formulae" [25, p. 73].

Max and Emmy Noether explained in a eulogy:

> For each work [Gordan] compiled volumes of formulae, very well ordered, but providing a minimum of text. His mathematical friends undertook to prepare the text for press and correct the printer's proofs. They could not always produce a fully correct conception and one often misses the deeper ground on which the considerations are laid. Only a few of his publications, especially the earliest, express Gordan's specific style: bare, brief, direct, uninterrupted theorems one after the other. [61, p. 5]

The "mathematical friends" were often Max Noether. He spoke from experience, meaning he wrote the published versions while he could not find "the deeper ground" for some of Gordan's claims. It may well be that newly certified French language teacher, Emmy Noether, wrote the text for Gordan's [20], shortly before her documented choice to study mathematics. So she too would be speaking from experience about not understanding the reasoning behind some equations. Anyway, the Noethers do not mean that early on Gordan gave his own proofs—they mean his early papers gave no proofs.

Noether's dissertation is more brief than Gordan's works and correspondingly more obscure. Computational algebraists Rebecca Garcia and Luis David Garcia Puente have worked on it with advice from Joseph Kung but so far it resists modern understanding. Despite advances in computerized algebra, even the results Noether published from her calculations cannot currently be understood let alone reproduced.

Noether at this time, like Gordan, gave vast calculations and made general claims but did not give recognizable proofs. Gordan died in December 1912. Emmy Noether kept his picture on the wall of her study [83, p. 124] as she went on to a new career, a new town, a new century.

13.3 A Göttingen Career

> In my Göttingen years, 1930-1933, she was without doubt the strongest center of mathematical activity there, considering both the fertility of her scientific research program and her influence upon a large circle of pupils. (Weyl [83, p. 54])

> [Noether] was especially popular with the Russian visitors; and when they began to go around Göttingen in their shirtsleeves—a startling departure from proper dress for students—the style was christened "the Noether-guard uniform." (Alexandroff [65, p. 352])

Understand that in Weimar Germany, that joke about a “Noether-guard” was a deliberate comparison to political youth groups which often functioned as street gangs. Like many jokes it drew on real anxieties. Russian sympathies were a major anxiety and no joke at all [39, 40].

Gordan was succeeded by two men who introduced Noether to the newer Dedekind and Hilbert styles of algebra: first Erhard Schmidt, then Ernst Fischer.

In September 1913, she announced her project reforming aspects of Hilbert’s algebra [47]. Anyone at the time would have found it ambitious, yet it pales compared to what she actually did. After publishing her dissertation and an article related to it the Berlin-based Crelle’s journal she shifted to the newer Göttingen-based *Mathematische Annalen* to complete the project in papers titled *Fields and systems of rational functions*, *The finiteness theorem for invariants of finite groups*, and *Equations with prescribed (Galois) groups*, [48–50]. Section 13.3.1 describes these.

Klein and Hilbert brought her to Göttingen in the Spring of 1915 to fill in for male *Privatdozenten* (unsalaried instructors) gone to war [12, p. 24]. This was the first teaching stage of a normal academic career and those two plus many other prominent mathematicians backed her for the title.[3] However the faculty refused to allow the title to a woman. There is a famous, though undocumented, story that Hilbert protested:

> I do not see that the sex of the candidate is an argument against her admission as *Privatdozent*. After all, we are a university and not a bathing establishment. [83, p. 125]

In 1919 after the Revolution and in the Weimar Republic she became *Privatdozentin*. The official announcement used the ending “-in” to make it a feminine noun. The promotion required presenting a piece of work. She chose the now famous *Noether Conservation Theorems*, see Sec. 13.3.2.

She was promoted to *nicht beamteter ausserdordentlicher Professor* in 1923. That is an adjunct Professor not on the faculty and without benefits such as a pension. The title granted her the right to officially direct dissertations. Stipends were arranged for her since the family money was nowhere near enough to live on. Memoirs often say she did not care about food or clothes but only cared for mathematics. Tollmien replies that, aside from whatever idiosyncracies Noether had, she could not afford nice food or clothes [76, p. 189].

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[3]When Norbert Wiener wrote to support Noether for a job in the U.S. he described biases against her in the euphemisms of the times: “sex, race, and liberal attitude” [24, p. 35]. Here “race” was a polite way to avoid saying Jew, and “liberal” a polite term for Marxist. The weight of these biases shifted over time as Noether and the forces around her changed. Anti-woman feeling was strong throughout, as Tollmien, [76], shows. But the public record is skewed because people try to look good. The stern discipline of the traditional, all-male university was easy to frame as a lofty ideal; so it was easy for reactionaries to avow. Anti-semitism, while widespread at every level of society, was especially associated with low class agitators so cultured people did not like to discuss it. And, like a cancer diagnosis, allegations of communism were best not discussed at all—in Germany or in the U.S.

In the early 1920s she did the work most widely mentioned when people talk about Noether today. She used relatively simple axioms on commutative rings to unify, simplify, extend, and strengthen classical facts about polynomial factorization, algebraic number theory, and algebraic geometry. The most important of these axioms is now named for her: the *Noetherian condition*. See Sec. 13.3.3.

She developed a technique from Dedekind much farther as her *Homomorphism and Isomorphism Theorems*. She declared this technique should organize much other mathematics—she names topology, for example [55, p. 104]—and really she meant all of pure mathematics [41].

This is the kind of thing Taussky-Todd meant when she said Noether "irritated people by bragging" [74, p. 84]. But Noether's vision is now accepted across a great deal of mathematics.

Alexandroff became one of many young men gathering around Noether in Göttingen. He shared her love of swimming:

> The Klie swimming establishment was expressly for men: womanhood was represented there only by Miss Emmy Noether and Mrs. Nina Courant. Both ladies daily used their exceptional right, no matter what the weather. [3, p. 114]

He and several other of these young researchers also met with her and discussed topology on visits to Brouwer's house in Laren, Holland [2, 41]. Note Brouwer too, by this time, intended to reform all of mathematics and not everyone found it easy to get along with him [78].

She had a large, warm, and growing circle of friends and collaborators. Their mathematical walks became famous. Saunders Mac Lane documents a three mile hike to the Kerstlingeröder Feld:

> Noether's enthusiasm for lecturing was not much impeded by days when the Institute was shut. I recall one day when the Institute was not scheduled to be open because of a state holiday. Noether announced that the class would go on just the same, but would take the form of an "*Ausflug*." So we all met on the steps of the Institute and walked the short distance out to the country through the woods to a suitable coffee house, talking about algebra, other mathematical topics, and Russia on the way. Evidently this great enthusiasm of Noether's was a major element in her considerable influence on algebraists throughout Germany. [37, p. 71]

She then applied her algebraic methods, centered on homomorphism and isomorphism theorems, to non-commutative rings to solve major problems in number theory, especially the high-powered branch *class field theory* [35]. This became the topic of her 1932 plenary address to the International Congress of Mathematicians in Zurich [59]. Weyl as President of the *Deutsche Mathematiker-Vereinigung* probably secured the invitation [67, p. 307].

The plenary address is often called the greatest honor of her career. No doubt she and her friends were delighted by it. But she had to know her extraordinary influence on world mathematics meant more than any address.

13.3.1 Noether's First Great Mathematics, 1913–1918

> What follows is an entirely elementary finiteness proof—using only the theory of symmetric functions—for the invariants of *finite* group actions, which at the same time actually gives *complete systems*; while the usual proof using the Hilbert theorem on module bases is only an existence proof. (Noether 1916 [49, p. 89])

Noether's paper *The finiteness theorem for invariants of finite groups* gives a stunningly astute statement of the theorem, which virtually proves itself once it is expressed in her way. Then she gives two different explicit routines, each under one page long, to calculate a complete system of invariants for any given finite group. She cites one of her favorite references, Weber's *Textbook on Algebra* [82, pp. 225ff.], for a very much longer pure existence proof using Hilbert's Basis Theorem. That proof gives no help in actually finding invariants.

Noether was keenly aware of outdoing Hilbert's method on this proof.

Today we can make her 1916 proof rigorous using the tools for group representation theory that she created 10 years or more later. In this sense it is a radical advance in clarity over her dissertation. Yet her own very brief description in 1916 sounds like she meant it as new symbolic method analogous to Gordan's, quite unlike her later tools. It is not clear specifically how she understood the proof when she wrote it [44].

Her related articles, *Fields and systems of rational functions* and *Equations with prescribed (Galois) groups* [48, 50], make progress on rational function fields and Hilbert's 14th problem but most especially on the *inverse Galois problem*. The basic problem is: given a finite group $\mathfrak{H}$, find an extension of the rational numbers with Galois group $\mathfrak{H}$. It is not yet known which groups $\mathfrak{H}$ admit solutions. Hilbert found a surprising sufficient condition on $\mathfrak{H}$ which Noether sharpened to a form still central to inverse Galois research today [72].

13.3.2 The Conservation Theorems, 1918

> What is to follow, therefore, represents a combination of the methods of the formal calculus of variations with those of Lie's group theory. (Noether [51, p. 235])

As to what Noether meant by *formal calculus of variations*, and the role of Sophus Lie, see Sec. 13.5.1 and 13.5.2.

Soon after Noether arrived in Göttingen, Einstein showed that in General Relativity (GR) the total energy-momentum flow into a point equals the total flow out (the flow has divergence 0 at every point). But this is very far from showing that the total energy-momentum content of a bounded region can only change by an equal flow of energy-momentum across the boundary. Roughly speaking, spacetime in GR can contract or expand inside a region, altering the energy-momentum content with no flow across the boundary. Klein and Hilbert claimed physics must deal with regions, not points, so Einstein's is not a proper conservation law. Hilbert conjectured that all *generally covariant* theories have this problem, [7, p. 103] [30, pp. 37ff.]. See also [68]. Einstein maintained this was no flaw: he claimed it is the best that gravitational physics can allow once you accept Special Relativity (SR) as locally correct.

Noether was called in since invariants are akin to conservation laws. She saw how Sophus Lie's geometric view of symmetries of differential equations applied to the equations arising in the calculus of variations settles the question in extreme, elegant generality. She actually proved two theorems:

1. For equations whose symmetries are parameterized by real numbers, the symmetries correspond exactly to conserved quantities. For a simple example known long before Noether: in Newtonian particle mechanics, the potential energy of a system is unchanged by translations along the x-axis if and only if momentum in the x-direction is conserved in that system. Note each such translation is determined by a single real number saying how far to translate.
2. Equations whose symmetries are parameterized by functions admit only trivial conserved quantities—roughly speaking you can get conservation of flow into and out of single points, but not into and out of regions. And this is the case in GR, since a symmetry in curved spacetime cannot be specified by merely giving one distance d in some direction; it must specify an entire coordinate transform over some region.

The first has huge practical value organizing conservation laws, and revealing new laws, in Quantum Mechanics and other fields [62]. But the real productive value of this first conservation theorem was only revealed with the later development of quantum theory.

In 1919, Einstein, Klein, and Hilbert all immediately saw the importance of the second theorem for GR. Einstein wrote about a note Noether had written on her way to this result:

> Yesterday I received from Miss Noether a very interesting paper on the generation of invariants. I am impressed by the fact that these things can be understood from so general a point of view. It would have done the Old Guard of Göttingen no harm to be sent back to school under Miss Noether. She really seems to know her trade! (quoted in [30, pp. 71f.])[4]

Her second Conservation Theorem confirms Hilbert's conjecture in such generality that it simultaneously vindicates Einstein's claim that his law was the best you could expect!

[4] Kosmann-Schwarzbach [30] has a great deal more on Einstein and Noether.

13.3.3 Homomorphism and Isomorphism Theorems

> The tendency to strict algebraization of topology on group theoretic foundations, which we follow in our exposition, goes back entirely to Emmy Noether. This tendency seems self-evident today. It was not so eight years ago. It took all the energy and the temperament of Emmy Noether to make it the common property of topologists. (Alexandroff and Hopf [6, p. ix])

Noether's best known proofs were published in the 1921 *Ideal Theory in Rings* and the 1927 *Abstract structure of ideal theory in algebraic number- and function-fields* [54, 57]. This is her axiomatic ring theory. These proofs are less explicitly cited in the literature than her Conservation Theorems for two reasons: There is no need to name her since the whole subject of *Noetherian rings* is named for her. And there is no need to cite her original articles since textbooks today still give essentially her proofs in her terms. Section 13.5.3 returns to Noether's importance in the rise of modern textbooks.

The work grew from Noether's report to the DMV on the state of the art in factoring *algebraic integers* and *algebraic functions*. These sophisticated but entirely concrete topics deal with integer polynomials in one variable, and complex polynomials in two variables. She describes her report as a complement to an earlier related report by her father, Max [52, p. 182].

The paper *Ideal Theory in Rings* [54] showed that classical results on polynomials hold in all Noetherian rings, and it immediately gave new results for the classical case of complex polynomials in two variables. These results are weaker than unique prime factorization. The paper *Abstract structure of ideal theory in algebraic number- and function-fields* [57] showed unique prime factorization is essentially equivalent to certain stronger axioms on a Noetherian ring. These stronger axioms are geometrically interesting in themselves—plus, they transparently fail for complex polynomials in two variables. So they show the limitations on the classical results for polynomials are unavoidable.

The factorization theorems were only part of her progress. More important for mathematics overall is that she proved them by her Homomorphism and Isomorphism Theorems.

Her Homomorphism Theorems replace equations $f(x) = y$ by homomorphisms $f : S_1 \rightarrow S_2$ between rings, modules, or other structures S_1, S_2. Choosing which structures S_1, S_2 to use amounts to choosing what information to make explicit out of all that is implicit behind the equations. Those theorems imply her Isomorphism Theorems, which explicate when one structure, S_1, carries exactly the same information as another, S_2, however different the original descriptions may have been.

Homomorphism and Isomorphism Theorems allowed Alexandroff and others to algebraize topology [41]. They, and their descendent methods, serve widely across mathematics today. Besides organizing classical material, they facilitate the discovery, proof, and teaching of new theorems. Wolfgang Krull called it

> Noether's principle: base all of algebra so far as possible on consideration of isomorphisms. [32, 4]

As a perfectly concrete example from number theory, Peter Roquette says:

> In my opinion, the main importance of Artin's Reciprocity Law (1927) is that it opens a new viewpoint on those classical laws, formulating it as an isomorphism theorem. (Quoted from personal communication at http://www-history.mcs.st-andrews.ac.uk/Biographies/Artin.html)

Reciprocity laws have been a mainstay of number theory ever since Gauss proved quadratic reciprocity: For any prime numbers p, q equal to 3 modulo 4, p is equal to a square number modulo q if and only if q is not equal to a square number modulo p; and if one of p, q equals 1 modulo 4 the either p and q are both square modulo the other or neither is. By 1920 many extensions were known to higher powers than squares, and to other algebraic integers in places of ordinary integers. Hilbert's Ninth problem was to generalize this reciprocity law to all powers and all rings of algebraic integers.

The problem is extremely intricate arithmetic, but it is no kind of abstract algebra – it is very concrete arithmetic. Emil Artin made huge progress by casting this arithmetic in terms of isomorphisms.

In the late 1920s, Noether turned her focus to non-commutative rings. Her device of *crossed product algebras* recalls her 1916 proof of *The finiteness theorem for invariants of finite groups* [49], but now using her Homomorphism and Isomorphism Theorems. The ideas in her 1932 talk in Zurich [59] have led so far into modern cohomological number theory we can do no more than cite [16, p. 157]:

> [Noether's] theory of crossed products and central simple algebras has been a main tool in class field theory [and] what we now would call the cohomology of number fields.

13.3.4 Expulsion from Germany

During the Nazi rise to power in 1933, Noether saw as well as Viktor Klemperer [27, p. 11] did how "day by day naked violence, denial of rights, the most horrible hypocrisy, completely unconcealed barbarity, are declared the law." So Noether let leftist students meet in the relative safety of her rooms [12, p. 80]. When books were stolen from the mathematics reading room Noether's rooms were searched "because she had once lectured on education in the Soviet Union" [69, p. 17]. She was

> literally driven out of one of the Göttingen pensions (where she lived and ate) by the demands of student leaders in the pension who did not want to live under the same roof with "a Marxist leaning Jewess." [5, p.107]

Many mathematicians tried to help her keep her job as Jews were driven out everywhere. It was no use. In April 1933 she lost the right to teach, and thus lost anything to live on but "a small inheritance (I never was entitled to a pension, anyway) which allows me to sit back for a while and see" [12, p. 47]. People sought to create places for her at Moscow University and at Somerville College, Oxford, [5, p. 109] [24, pp. 30ff.]. The first to succeed was Bryn Mawr.

Weyl tells how he and she and others prepared to leave Germany:

> I have a particularly vivid recollection of those months. Emmy Noether, her courage, her frankness, her unconcern for her own fate, her conciliatory spirit, were in the midst of all the hatred and meanness, despair and sorrow surrounding us, a moral solace. [83, p. 132]

We must forgive him saying in his eulogy to her "she did not believe in evil—indeed it never entered her mind that it could play a role among men" [83, p. 151], and forgive Ruth McKee repeating it [63, p. 144]. Both were grieving and were moved by her selfless generosity of spirit. They were not thinking clearly. Emmy Noether knew evil.

13.4 Bryn Mawr

> Meeting Noether was one of the great things of my life. (Taussky-Todd [63, p. 145])

> We can be the feminists for her. Let her be Noether. (math educator Sheila Tobias, speaking at Case Western Reserve U. in 1999)

Noether's first official doctoral student was a woman, Margarethe Grete Hermann, in Göttingen 1926, and Noether enjoyed her women students at Bryn Mawr. She did find the Bryn Mawr "girls" too attached to concrete calculations and unfamiliar with abstract algebra—just as she found the research fellows at Princeton [36, p. 204]. She was used to mathematicians being that way everywhere.

For a while Noether gave weekly lectures in Princeton: "at the Institute and not at the 'Men's' university where nothing womanish is allowed" as she wrote to Helmut Hasse back in Germany [36, p. 204].

Olga Taussky who worked with Noether in both Göttingen and Bryn Mawr gave subtle expression to Noether's views on women in the academy:

> Emmy was not uninterested in the many problems women face. I know that she was concerned already in Göttingen. I think it was through her, but am not completely certain about it, that I learned about the IFUW, the International Federation of University Women, of which the AAUW is a branch. I recall that at the Congress in Zurich in 1932 she attended one of their meetings when they invited her, or maybe she only mentioned the invitation to me. In any case I do recall that she said that one ought to attend such functions. [74, p. 91]

That whole essay is worth reading for the deeply felt description of the wonder, but also the difficulty, of being a woman student of Noether.

At Bryn Mawr, Noether's students and colleagues ardently supported women's education and careers. Her work developed rapidly for the short time she had remaining. The mathematical walks she enjoyed in Göttingen continued in the new world. Ruth Stauffer McKee, Noether's doctoral student at Bryn Mawr, reports the Noether group one day crossing a field near the college:

> I soon realized we were headed straight for a rail fence. Miss Noether was immersed in mathematical discussion and went merrily on, all of us walking at a good clip. We got closer and closer to the fence. I was apparently the weak sister, concerned mostly in how we would handle the fence. For those of us in our twenties it would be no problem but, from my point of view, however would this "old lady," fiftyish, handle the fence? On we marched right up to the fence and without missing a word in her argument she climbed between the rails and on we went. [63, p. 144]

Her niece Emiliana Pascal Noether recounts the shocking news:

> In the spring of 1935 she entered Bryn Mawr hospital to be operated on for the removal of a tumor; she seemed to be recovering well, when she died suddenly on April 14 at the age of fifty-three. Thus ended the life and career of this remarkable woman, whose death was mourned by her friends and colleagues not only as a loss to the work of mathematics, but also on a deep, personal level. [45, p. 5]

13.5 Noether's Impact: The Contrast of Two Centuries

> In these days the angel of topology and the devil of abstract algebra fight for the soul of each individual mathematical domain. (Weyl [84, 500])

Weyl is a vital source on Noether, but has his limitations. While his sharp mathematical mind put him among the first to appreciate her results, he could never reconcile his mathematical heart to abstract algebra. And while he had no objection to women in mathematics, nothing in his life prepared him to meet a woman genius—see Duchin's *The sexual politics of genius* on Weyl's and others's views of Noether [14, esp. p. 28]. Weyl saw abstract algebra as one step removed from mathematical substance, and he exaggerated Noether's dependence on others, especially Hilbert.

He sincerely valued and supported her work. When a professor complained of the "Hebrew" Noether and her abstraction Weyl compared her to Dedekind:

> As little as I personally have to do with abstract algebra, yet I rate her achievements and importance very clearly higher than do you. I am impressed specifically by Noether as her problems become ever deeper and more concrete. Why should she, the Hebrew, not do as well with what achieved so much in the hands of the "Aryan" Dedekind? [23, p. 9].

With the benefit of hindsight we might say it is only fair to compare her to Dedekind. But in 1933 Dedekind was long-tested, and Noether herself had done much to establish the full scale of his importance [11]. In contrast Noether's entire career in modern algebra only went back to 1916. This was extremely high praise at the time, seriously offered. But, again, Weyl had his limitations.

13.5.1 Hilbert, Gordan, and Abstract Algebra

> Her dependence on Gordan did not last long; he was important as a starting point, but was not of lasting scientific influence upon her.... [By 1913] the transition from Gordan's formal standpoint to the Hilbert method of approach was accomplished. (Weyl [83, pp. 122f.])

Weyl is a valuable historian of mathematics, but more precisely of Hilbert's mathematics, and he regarded Gordan as Hilbert's enemy [85, p. 622]. He was certain Hilbert's method alone led Noether to her great work.

Weyl was wrong about that. Noether indeed benefitted from Hilbert's style, but also from Lie's, and more from Dedekind's. And she kept a key idea from Gordan.

As Corry says, Hilbert's axioms are never abstract:

> Hilbert's own use of the axiomatic method involved, by definition, an acknowledgment of the conceptual priority of the concrete entities of classical mathematics, and a desire to improve our understanding of them, rather than a drive to encourage the study of mathematical entities defined by abstract axioms devoid of immediate, intuitive significance. [10, p. 170]

Gordan's method was abstract in this sense. Far from immediate intuitive meaning; he insists "no meaning can be assigned" at all to some of its steps [18, vol. 2, p. 10]. He knew that some concrete calculations of invariants first become feasible when we use these abstract tools.

Noether, too, created abstract tools, such as the *crossed products* used today in *group cohomology* [38]. Remote from intuitive arithmetic, they organize concrete arithmetic calculations [43].

Noether knew she made such tools far more productive than Gordan ever did. She eagerly forgot Gordan's symbolic method [12, p. 18], [5, p. 99]. But she would object to Weyl asking:

> What then would [Gordan] have said about his former pupil Emmy Noether's later "theology," that abhorred all calculation and operated in a much thinner air of abstraction than Hilbert ever dared! [83, pp. 118f.]

She abhorred *inefficient* calculation, with hundreds of intermediate steps, when skilled algebra could quickly yield the result you really want. She equally abhorred thin, unproductive abstractions. Gordan taught her that the right abstract tools can get otherwise intractable calculations actually done.

13.5.2 "It is all already in Dedekind": Modesty or Bragging?

> Emmy Noether always said that the whole theory of ideals could already be found in Dedekind and that all she had done was to develop Dedekind's ideas. (Alexandroff [4, p. 299])

Noether assiduously cited earlier work on anything she did. But she also gave surprising credit for her own ideas. We quoted her above calling her Conservation Theorems "a combination of the methods of the formal calculus of variations with those of Lie's group theory" [51, p. 235]. Some historians say she was being modest, but we know she was not that. Taussky-Todd, quoted in Sec. 13.1.1 saying Noether irritated people by bragging, also says:

> She came to appreciate Dedekind's work to the utmost, and found many sources of later achievements already in Dedekind. Occasionally she annoyed even her friends by this attitude. [74, p. 81]

Noether *was* bragging. She saw what others missed. Conservation laws? Those are invariants of group actions. So of course one would use Lie's methods. And the rest is mere formalities. That is, they were mere formalities to Noether, even if others had somehow missed seeing them. She was happy about this.

As to Dedekind, even he might have been puzzled if he could have read her paper *Abstract structure of ideal theory in algebraic number- and function-fields* where she says her Isomorphism Theorem occurs "in a somewhat more special form" in his work [57, p. 41n]. Noether grasped Dedekind's insight that fields, and rings, and modules are all additive groups with further structure. She grasped it more deeply than anyone before her, including Dedekind. But she went further to see fields, rings, modules, and, indeed, modules over any one ring R, as each having their own proper sense of *homomorphism* and so of *isomorphism* corresponding to their further structure [41].

Dedekind's prototype Homomorphism Theorem is just a way to count the elements of finite groups. He gives his analogue to Noether's Isomorphism Theorem only for non-zero additive subgroups of the complex numbers—which can never be finite. Since his theorems apply to different things neither one implies the other. Noether proves her Isomorphism Theorems from her Homomorphism Theorems.[5] Dedekind's single pair of unrelated theorems became Noether's infinite family of theorem pairs, with one in each pair implying the other [41, pp. 221f.]. And yet, according to her own statements, she found this in Dedekind.

> Dedekind's work was a veritable treasure field for a person with Emmy Noether's powers of discernment. [17, p. 139].

Call it bragging. Call it generosity. Just know that Noether was happy about these things. Dedekind certainly saw more than he ever found means to say. Every creative thinker does. Noether could say what he saw; and she saw more there than he did. She had none of the historian's interest in recording the precise evolution of ideas. She had a generous researcher's interest in learning all that was known from the best sources, acknowledging them, and going beyond.

[5]For each ring, R, notably including the group ring for any group, Noether derives an Isomorphism Theorem specific to R-modules from a corresponding Homomorphism Theorem.

13.5.3 Writing and Teaching Mathematics

> The days are gone when one fondly described one's professor with "He said A, wrote B, meant C, and D is correct." (Hel Braun [8, p. 53])

People who only read the highlights of 19th and early 20th century mathematics may not realize how disorganized mathematics as a whole was then.

Hel Braun began studying mathematics at Frankfurt in 1933, just too late to meet Emmy Noether, but was fascinated by her reputation. Braun found that "In my student days university mathematics rested strongly on being mathematically gifted. Logic and notation were not so well established" [8, p. 53]. More fully:

> This largely goes back to the algebraists. University mathematics became, so to say, more "logical." One learns methods and everything is put into a theory. . . . Professors give lectures so that a sound understanding suffices for the student to follow, and special giftedness is no longer so extremely important. [8, p. 13]

Max and Emmy Noether describe Paul Gordan very much the way Braun describes the lectures of her student days:

> His own knowledge rested less on deep knowledge of other's works – since he read them very little – than on an instinctive feel for the ways and goals of mathematical efforts. . . . He never did justice to developing concepts from the fundamentals. In lectures as well he entirely avoided fundamental conceptual definitions, even that of *limit*. . . . His lectures rested on lively expression and the power gained from his own studies, rather than systematic rigor. [61, p. 36]

Compare this to Emmy Noether's "formal calculus of variations" of 1918. Are her differential operators defined by limits? Are they defined by formal derivatives? Her proofs are not explicit enough to tell.[6] Peter Olver's book [62] gives elegant expression to Lie's and Noether's ideas using *jet spaces*. But Lie and Noether never had those. Those combine analysis with algebraic techniques Noether pioneered in the 1920s, especially quotient modules as in her Homomorphism Theorems.

Noether was the leader in principle and in person in the new algebraic style. The hugely influential 1930 textbook *Moderne Algebra* of van der Waerden declares on its title page that it draws on lectures by Noether and Artin [80]. Van der Waerden was Noether's student. And Artin worked on abstract algebra with Noether in 1921–1922.

[6] She clearly ignores analytic questions of existence of solutions. She may believe these are easily answered when the integrands are "analytic or at least continuous and continuously differentiable finitely often" (meaning infinitely often) [51, pp. 236]. She may consider those questions irrelevant since that assumption lets her use formal Taylor series in the Eulerian style she knew from §§ 5–10 of [28]. Or she may echo a remark by Hilbert about "purely formal" calculation which seems to mean ignoring details for the moment [26, p. 470].

Affordable textbooks became the standard way to study mathematics. In Erlangen Noether studied leading journals and the lavishly bound *Encyklopädie der mathematischen Wissenschaften* in the University reading room. Braun says of the 1930s:

> In my student time there were few textbooks, many were expensive and one used them only in the library to look things up. [8, p. 13]

The growing number of mathematicians, faster cheaper travel, and new print technology all made it both possible and necessary to unify styles and standards in mathematics. As an amusing sidelight on this, it is easy today to type up close replicas of Noether's original articles because the standard LaTeX mathematics fonts are close to Springer fonts of her time.

The actual unification was largely shaped by Noether. The paradigm of standardized 20th century textbook mathematics, Bourbaki's series the *Elements of Mathematics*, agreed with Braun in taking it back to the algebraists and to Noether. Bourbaki member Jean Dieudonné says:

> The Bourbaki treatise was modeled in the beginning on the excellent algebra treatise of van der Waerden. I have no wish to detract from his merit, but as you know, he himself says in his preface that really his treatise had several authors, including E. Noether and E. Artin, so that it was a bit of an early Bourbaki. [13, p. 136]

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Chapter 14
In Her Own Words: The Personal Perspectives of Mina Rees

Amy Shell-Gellasch

Abstract Mathematician Mina S. Rees (1902–1997) broke many barriers during her long and varied career. Known for being a strong and dedicated leader, she was also an insightful and compassionate educator. She wore many hats over the years, all of them traditionally male: mathematics professor, college dean, college president, second in command of a war-time research panel, deputy science director of the Office of Naval Research, pioneer in early computing. Significantly, she was the first female president of the American Association for the Advancement of Science. She accomplished all this with personal strength and integrity. Though she was outspoken when it came to research and education, she rarely spoke of her personal life. In this chapter, we will explore her amazing career, laying special focus on her personal journey. Rees wrote a "Biographical Letter" in the *AWM Newsletter* in 1970 and gave several interviews in which she did share several personal stories. These stories, along with other personal comments she made over the years, will guide our look at the groundbreaking career of a remarkable woman. Many of her sentiments are still relevant today as education strives to service an ever-diversifying student body.

Keywords Mina Rees • Female mathematicians • History of mathematics • Wartime research • Graduate Education

14.1 Introduction

> Now, by definition, a college has a mathematics department, so at a college for women, you have to have women in mathematics! At those [women's] colleges, women were not discouraged from studying mathematics. In fact, it was one of the most popular majors at Hunter [College] when I was there. Later, after I had my Ph.D. and was teaching, I knew virtually all the women Ph.D.s on the East coast, and they were teaching at these colleges; that's where women Ph.D.s made their careers. So I didn't meet any discouragement at all when I was going into math. Indeed, I didn't know it was a peculiar thing to do. I did what

A. Shell-Gellasch (✉)
Eastern Michigan University, Ypsilanti, MI, USA
e-mail: amy.sg@earthlink.net

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everybody did: I picked the field that I found most interesting and decided to major in it. It never occurred to me that there was anything the matter with that.
Mina Rees, in *Mathematical People* [3, p. 258]

After Grace Hopper, Mina Rees is possibly the best known female name in the history of early computing. However, Rees is known for many other accomplishments, many of which were firsts for a woman: the first dean of the Division of Graduate Studies at the City University of New York (CUNY), first president of CUNY's Graduate School and University Center, first female president of the American Association for the Advancement of Science, and first recipient (male or female) of the Mathematical Association of America's Award for Service to Mathematics (later called the Gung and Hu Award). Rees had a long and varied career in mathematics, academia, grant administration at the federal level, and education reform at all levels. To give a complete biography of her education and career would take us too far afield, and biographical information can be found in many places. As a complement to what can be learned about Rees elsewhere (see, for example, [12]), this study will provide a brief overview of her career with special care given to her personal recollections and opinions.

14.2 Becoming a Mathematician

14.2.1 Early Life and Education

Although Mina Rees' professional work led her to crisscross the country at various times in her career, her academic life started in and repeatedly returned to New York City. Born in Ohio in 1902, she was raised in New York where she was a promising student. A junior high school teacher suggested Rees take the entrance exam for Hunter College High School. She did and was duly accepted. Affiliated with Hunter College, Hunter College High School was a tuition-free public school for gifted young women that recruited across the country. Rees graduated valedictorian in 1919. Rather unique for the time, but not unusual for a female institution, Rees took four years of mathematics; the curriculum, however, stopped before trigonometry [4].

Rees continued her studies at Hunter College, also a tuition-free women's institution. She excelled at Hunter academically and was involved in numerous campus activities, including service as editor-in-chief of the yearbook. Having enjoyed mathematics in high school, Rees continued to study mathematics: "[w]hen I went to Hunter College, I found that the mathematics department was where I wanted to be. It wasn't because of its practical uses at all; it was because it was such fun!" [3, p. 258]. Given Rees' abilities in mathematics, the college offered her the opportunity to teach a laboratory trigonometry course her sophomore year. To prepare, Rees enrolled in a course on surveying that summer at Teachers College, Columbia University, an early indication of her dedication and commitment to quality teaching. During her next three years as an undergraduate, Rees was also a paid part-time instructor at the College. She graduated in 1923 with a degree in mathematics *summa cum laude*, and was a member of Phi Beta Kappa and president of the student body.

14.2.2 First Career: Teaching Mathematics at Hunter College High School and Hunter College

Following graduation, Rees was again asked to teach at Hunter College, this time as a full-time instructor. Although it was not an uncommon practice at Hunter for an instructor to have only a bachelor's degree, Rees thought it was not well advised. She felt strongly that the college was making a mistake in this practice, even though she did have three years of teaching experience, and declined the offer. Instead, she took a position as an assistant teacher back at Hunter College High School and simultaneously enrolled at Columbia University as a full-time graduate student. She enrolled in both mathematics and law courses, having also developed an interest in the law.

While an undergraduate, Rees had studied abstract algebra out of a textbook by L.E. Dickson. She fell in love with the topic and set her sights on a doctorate degree in mathematics.

> After I had my bachelor's degree, I studied at Columbia. When I had taken four of their six-credit graduate courses in mathematics and was beginning to think about a thesis, the word was conveyed to me—no official ever told me this, but I learned—that the Columbia mathematics department was really not interested in having women candidates for Ph.D.s. This was a very unpleasant shock [3, p. 258].[1]

She elaborated on this in a personal interview with historian of mathematics Uta Merzbach in 1969: "Columbia really didn't want women in its student body. They were very nice to me when I was working for my master's degree. That was decent for a woman" [8]. This was Rees' first formal experience with sexism. As noted in the opening quote, having attending both an all-female high school since eighth grade and a women's college, she had not been subjected to explicit or implicit sexism or bias. She was not guided into a more lady-like area of study, as may well have happened if she had attended co-educational institutions. Referring to her experience at Columbia, Rees noted, "[t]hat was the only episode that raised a question about the appropriateness of mathematics as a field for women before I had my Ph.D. It was a really traumatic affair for me" [3, p. 258].

Rees changed course and received her master's degree from Teachers College, Columbia University in 1925. Degree in hand, she felt she could now join the Hunter College faculty with the appropriate background. As mentioned earlier, Hunter

[1]The quote (from 1985) continues, "Of course, this is certainly not at all true of the mathematics department at Columbia now."

remained an integral part of her academic and professional identity throughout her life. Even though she was a respected and impactful instructor at Hunter, she had not given up on her goal of obtaining a doctorate in mathematics. Rees thus began to lay the groundwork for studying mathematics with Dickson. She saved her paychecks and by 1929 felt financially secure enough to head to the University of Chicago to study under him. Always the planner, Rees did not resign her position at Hunter College, but instead took a leave of absence (or was eligible for sabbatical from her combined years of teaching; sources vary). This was well planned indeed, since the Great Depression was just a few years away. This leave of absence would ensure that Rees had a job waiting for her back at Hunter when she returned in 1931 as Dr. Rees.

14.2.3 Pursuing a PhD: Rees at the University of Chicago

Rees' move to Chicago is an interesting story and sheds much light on her as a person. Clearly, she felt there was a right way and a wrong way to do things. As was noted earlier, her insistence on being academically prepared for her teaching positions is evidence of this. But she also had a non-traditional, one might even say iconoclastic, side to her. She had set her mind on studying algebra, in particular division algebras, with Dickson. She then moved to Chicago without applying in advance to the university, but simply registered for classes upon arrival. It is not clear that she had even contacted Dickson about working with him when she enrolled at the University of Chicago. In fact, when she arrived she found out that he had returned to his earlier study of number theory and was no longer working in the field of divisions algebras in which she was interested. Yet after meeting Rees at the official inauguration dinner of the university's new president, at which Rees represented Hunter College, Dickson agreed to take her on as a student in division algebras. One wonders what was said, during what must have been a brief discussion, to encourage Dickson to take on this unknown student in a field with which he thought he had finished. Nevertheless, Dickson's attention was then focused firmly on number theory, with the result that Rees was ultimately "virtually self-educated" in her chosen field. As Rees described it,

> I decided that Dickson was the greatest man in the world and Chicago was undoubtedly the mecca of all algebraists, so without mentioning it to Chicago, I just went out in [1929] and turned up [. . .] I just informed him I wanted abstract algebra, and there just wasn't any work going on in abstract algebra at Chicago while I was there, so I am virtually self-educated. It was the craziest arrangement [8].

Besides Dickson's fame as an algebraist, Rees may have had additional motivation for choosing to work with him. The University of Chicago, and Dickson in particular, was far ahead of other institutions in granting advanced degrees to women. Between 1900 and 1940, Dickson advised 8% of all women PhDs in mathematics in the U.S. and 40% of those at Chicago [5, p. 44].

Rees worked hard and completed her dissertation *Division Algebras Associated with an Equation Whose Group Has Four Generators* in December 1931, in just five semesters. This research was the final and concluding segment of Dickson's work on associative division algebras. However, the constructive approach Dickson had employed in his work had by then been superseded by the approach taken in the work of Emmy Noether in Europe. Thus Rees' research most likely would not propel her into a high-powered research career or into a position at a prestigious university. Dickson may have given her this problem, which he probably knew she was capable of completing with minimal guidance on his part, to allow her to finish her degree and return to her position at Hunter. At the time, one's advisor and position upon completing a PhD was mostly determined through what Saunders Mac Lane termed the "old boys network" [12]. Rees was already set with regard to a position, so the cutting-edge dissertation may have been deemed unnecessary.

14.2.4 Returning to Hunter

Rees returned to Hunter in 1931; she was promoted to assistant professor in 1932 and associate professor in 1940. During this time, she immersed herself primarily in teaching and college duties. She also attended numerous mathematics conferences, where she met and built relationships with many prominent mathematicians. One of her joys was listening to other researchers discuss their projects, which allowed her to develop a broad overview of mathematical research in the United States. Little did she know at the time that her interest in new research developments would be a key factor in her future career moves and successes.

14.3 A Career in Service and Leadership

14.3.1 The Applied Mathematics Panel, 1943–1946

Had World War II not broken out, Rees most likely would have continued at Hunter, quietly instilling a love of mathematics in generations of students. But as happened to many women during the war, opportunities arose that were completely impossible just a few years earlier. And like many other women, Rees was ready when the call came. Describing this time in her life, she said, "I enjoyed teaching, and I was a very good teacher and I had a wonderful time with the students. It was ten years later [after returning to Hunter from Chicago] that Pearl Harbor occurred, and then I became uncomfortable the way most people did. I wanted to get into something that was relevant to the war" [8]. Rees joined the war effort in 1943 and her carefully planned career took a turn that would land her on the national and even international stage.

Fig. 14.1 Rees and Richard Courant at his retirement party from NYU, 1965. Photo Courtesy of the Graduate School and University Center Archives, CUNY.

In that year, less than two years after the United States entered World War II, the Applied Mathematics Panel (AMP) was created under the Office of Scientific Research and Development (OSRD) in order to facilitate and direct research in mathematics and related fields vital to the war effort.

Richard Courant suggested Rees to AMP Director Warren Weaver as a person who would be of value to the panel, both mathematically and administratively. Rees reported, "[I]t was Courant who was responsible for my being invited to join the staff of AMP as a civil servant" [11, p. 16]. Rees went on to describe how she got the position (Figure 14.1):

> It was not because I was an applied mathematician—my degree was in Abstract Algebra; it was not because I was a woman—there was no equal opportunity then. It was the good old buddy system. Let me explain.
>
> [. . .] In the summer of 1930 I attended my first summer meeting of the mathematicians here at Brown [University]. What I remember most clearly about that meeting was that I had breakfast with Marston Morse and G. D. Birkhoff. I found the experience overwhelming, and I was enchanted with mathematicians and, at least partially because of that, with mathematics. When I returned to New York, I continued my attendance at meetings, both winter and summer. And so it came about that, when Courant was visiting lecturer of the Society, I met him at a meeting, and continued my acquaintance with him when he came to NYU. Though I was not a research mathematician and though I soon learned that I couldn't understand much at the meetings, I did find them useful in giving me some idea of

> the directions that mathematical research was taking. [...] When AMP was being organized Courant recognized that Dr. Weaver would need administrative help as well as mathematical help, and suggested my name [11, p. 16].[2]

Rees thus once again took a leave of absence from Hunter College to join the AMP, first as a technical aide to the panel, then as secretary of the panel, and later as Weaver's executive assistant.

Rees summarized the need for the AMP as follows:

> [T]he Applied Mathematics Panel was established in recognition of the fact that many of the components of the Office of Scientific Research and Development needed mathematical assistance that was not available to them within their own shop [...] it wasn't possible for each component to have a range of mathematicians who could take care of all the kinds of problems that came up. After [OSRD] had been in operation for a year, they decided they needed a sort of stable of mathematicians who would be available to all of them and to the military [8].

The panel was composed of several prominent mathematicians including Courant and Oswald Veblen and was housed in the Empire State Building. The military brought problems of immediate importance to the war effort to the panel. For example, the problem of aiming weapons from a moving platform such as an airplane ("fire control") needed to be conquered. Several research groups, primarily at universities, were created across the country to work on such problems. These problems would first be evaluated by the technical aides, most often by Rees, to determine if they could be addressed quickly and constructively. As she noted, "often you were asked to perform a miracle which wasn't quite within our capacity" [8]. If the problem was deemed solvable in short order, it was sent to one of the research groups.

But Rees' involvement did not end there. Rees herself defined a technical aide as "a government employee who represented the government in dealing with what we called contractors. [...] We had university organizations all over the country who had contract[s] with the Applied Mathematics Panel to do mathematical jobs that were assigned to them" [8]. Importantly, she went on to state that "I think this was the beginning of the notion of the university contractors" [8]. In addition to taking care of endless administrative details, Rees described her role as follows:

> The job involved contact with the work going on under all contracts and attendance at all Panel meetings. There were trips to military installations, including headquarters in Washington, in the company of appropriate contract personnel, to clarify the problems we had been asked to help with, to determine the likelihood that we could do something useful, and to formulate recommendations to the Panel which met weekly [11, p. 16].

Rees not only evaluated the initial concern, she worked closely with all the research groups to coordinate and facilitate the research. In this role, she traveled widely to consult with the research groups. For security reasons, research groups were not always aware of the military necessity of their research. Sensitive projects were broken into smaller components that different groups would work on. Rees

[2] Rees did in fact co-author a research paper with Courant and E. Isaacson, published in 1952 [2].

then brought those pieces together in order to pass timely solutions back to the military. Her knowledge of research trends and the researchers themselves made Rees invaluable to the panel: "I was the secretary to this Panel, which gave me a central opportunity to understand about all the problems that came in either to Warren Weaver or to me." In the Merzbach interview [8], Rees elaborated:

> I was in [a] central position with regard to the military problems that required or hopefully could be handled with some mathematical assistance. Of course, as you well know, the mathematical nature of a problem is abstracted from its origin, so we would often have problems coming from one group of users which were the same mathematical problems that came in from others, so we served as a communication link, even between parts of the Navy. I spent a good deal of my time telling the Bureau of Ships what the Bureau of Ordnance was doing, and things like that. It was a very intellectually interesting job. Of course, you became terrifically involved in the urgency, the need to solve these problems, and to get the weaponry out and so on.

Even though Rees felt her work on the panel was incredibly worthwhile, that work was not without its negative aspects. In a letter to Courant dated December 1943, Rees confided her frustration over the change in her status in comparison with the prestige and authority she had as a professor at Hunter College:

> I want to tell you about something which is making life a bit difficult for me. [...] As you know, I am accustomed to the lordly status of a college professor. Moreover, at Hunter my position is unassailable, I expect to participate in important decisions, and no one would dream of asking me if I were somebody's secretary.
>
> I grow a bit weary of that assumption in my present job (and the question, "are you Weaver's secretary?") [... T]he loss of prestige and professional dignity, and of the opportunity to use what special knowledge and ability I have seems a high price to pay for a sense of doing something useful toward winning the war, and for the very real pleasure I get out of many aspects of the work [12, p. 59].

She went on to ask that when Courant introduced her to people, especially at meetings, he please introduce her as "Dr. Rees" to try to avoid the assumption that, as a woman, she could not possibly be the person running the meeting. This situation may seem at odds with how well respected she was in her role by the end of the war. But she was in a significant administrative role in 1943, and women were simply not seen in those positions at that time. And although she enjoyed the position itself, she was no longer actually doing mathematics. In fact, in a 1985 interview Rees lamented that "I don't think it's possible once you have left mathematics to get back into it" [3, p 260].

The administrative nature of Rees' job lay in the fact that AMP research projects were handled through the government procurement contracts system then in place. At that time, there was little funding of scientific research by the government and no other system to handle it. The contracts administered by the AMP soon became the foundation of today's well-established, mature system of federal support of research. But at the time, this was all new territory. Given Rees' unique role, she in essence molded the scope and style of early government grant funding for both pure and applied research. By the end of the war, Rees was widely acknowledged for the expertise and influence she had exerted in mathematical research for the war. In 1948, Rees and Weaver each received the King's Medal for Service in the Cause of Freedom from Great Britain and the President's Certificate of Merit from President Harry Truman. Rees, along with Grace Hopper, was also widely linked with the new electronic computers that were developed as part of the war effort. After the AMP closed at the end of the war, as Rees yet again headed back to Hunter College, she took with her a deep interest in this new field of applied mathematics.

14.3.2 The Office of Naval Research, 1946–1953

One of the often overlooked results of the scientific efforts during the war, and the AMP in particular, was the migration of some mathematical research away from what is now called pure research toward applied research. While many researchers returned to their "pure" endeavors after the war, the die was cast for the now-familiar interplay between pure and applied, as well as the funding of such research at the federal level. Rees described this change in 1969:

> I don't really know too well what went on in what was called applied mathematics before World War II. Warren Weaver had been identified with this notion out at Wisconsin, and Thornton Fry came out of that same background, and was the one who established the concept at Bell Labs, of having the Applied Mathematics Division [of the Office of Naval Research].
>
> Now the thing they were talking about was much more restricted when they said applied mathematics than what we mean now. I think what we mean now is essentially anything where you use mathematics in [attacking] a real problem, and [this] calls on all branches of mathematics. There just is nothing that is excluded, I think that does go back to World War II [8].

In the autobiographical letter in the *AWM Newsletter* in 1979, published by the Association for Women in Mathematics (AWM), Rees described why her time on the AMP was also decisive for her career:

> First, it broadened my awareness of unfamiliar fields of mathematics and my contacts with mathematicians; and, second, because it greatly increased my understanding of the character and activities of many of our major educational institutions and of the structure and operations of the government including the military establishment. In short, it gave me the kind of experience that made it appropriate for me to be invited to become head of the mathematics research program of the Office of Naval Research when that Office was established after the war [11, p. 15].

Rees further commented in 1978 that "[t]he wartime performance of these [AMP] scientists won for science the high regard of the military establishment and of Congress and the recognition that post-war expansion of research in the sciences was a national requirement" [10, p. 102]. Her role in this did not go unnoticed. Even before she had settled back into the post-war world, she was offered a high-level position in the newly formed Office of Naval Research (ONR) in 1946.

> My work with the Panel lasted until the end of the war in 1946. It gave me familiarity with the work of much of America's most able mathematicians; and it gave me considerable understanding of the changes that were occurring in mathematics as a result of experiences in World War II. [. . .] When the Office of Naval Research was established after the war, it was natural that my name should be suggested, along with others, to head the mathematics component of the new Office [11, p. 16].

In an interview with historian of mathematics Constance Reid in 1973, Rees added, "I had been receiving calls from Naval officers and people involved in setting this [ONR] up [. . .] so I knew what was going on. It wasn't a call out of the blue exactly, except I hadn't anticipated that I would be doing it" [9]. Rees had doubts about the effectiveness of the whole idea of government funding of basic research, but after consulting friends and colleagues she decided to accept the offer.

The government, with the Navy in the lead, did not want to lose the impetus and expertise gained in scientific research during the war. The ONR would be the primary, in some senses the only, government agency involved in granting contracts for scientific research until the founding of the National Science Foundation in 1950. Rees would be at the forefront of this movement as the head of ONR's Mathematics Branch from 1946 to 1949, Director of the Mathematical Sciences Division until 1952, and Deputy Science Director until she left ONR in 1953.

Rees was initially concerned that the successes and momentum of the wartime work would not carry over to peacetime. During the war, people worked together for a higher common purpose. Would that still be the case once the war was over? Or would academics shy away from government funding, concerned over government involvement? In a rare comment about her role as a woman in a man's world, Rees addressed two concerns she had about the new position.

> It was at this time that my being a woman raised some serious doubts. But, in due course, I was invited to become head of the mathematics research program of ONR. I did raise a question about the possibility that my sex might prove a deterrent to my success. But we decided to take a chance.
>
> My sex was only one of the problems that I had. I very much doubted that the mathematicians would want to receive support for their research from a military organization after the war was over. Initially, this judgment was right. But, as time passed, mathematicians found the program a very desirable one. And I found the ONR experience an exciting one [11, p. 17].

Much of Rees' work at ONR resembled her work on the AMP, establishing research programs, granting research funding, and traveling widely. But at ONR, she was eventually able to go further. She pushed for and gained approval from top Navy brass to expand the scope of research beyond present-need applied mathematical, computer science, and scientific questions to longer-range pure questions; that is, to research that may not have immediate uses, but would, nonetheless, be valuable to the greater mathematical and scientific world. As has been seen time and again, pure research often produces important applications years later. Rees later stated that "[i]n the early days, we recognized that, until a National Science Foundation (NSF) was established, ONR had a special obligation to provide for the balanced support and growth of mathematics research in the United States" [10, p. 110].

Through ONR, Rees was also able to promote educational advancement by establishing initiatives such as graduate student and post-doctoral research grants and by helping to build research programs in areas of the country and at institutions not already at the center of research activity. As Rees explained it very succinctly to Constance Reid,

> [t]his [research contracts] was a new thing that was carried over after the war into the whole ONR and the whole program that still exists for the support of research. At that point it was the support of research in support of the war effort. Later it was support of basic research. But the notion of supporting university scientists by a contract with the government was new [9].

This was an understatement; the federal government and university research were entirely separate at the time, and as previously mentioned, getting researchers to be comfortable accepting government money was one of her early hurdles. By the time she left ONR in 1953, Rees had helped broaden funding of scientific research to include funding in academia in a wider context. Joachim Weyl (son of Herman Weyl) stated in an article about Rees' election as President of the American Association for the Advancement of Science that

> ONR made her the architect of the first large-scale, comprehensively planned program of support for mathematical research: she pioneered its style, scale and scope. What took shape in ONR stood as a model for the subsequently established Office of Scientific Research of the Air Force and for the Office of Ordnance Research of the Army. Also, the policies that the National Science Foundation followed in its support of mathematical research owe much to her advice and that of members of its staff who had worked with and after her at ONR [13, p. 1149].

Rees herself indicated how unique the ONR was in the years before the NSF as well: "[ONR] really acted in an important way like the National Science Foundation. [. . . I]t was a mechanism for supporting basic research at universities, and one of my early achievements was to get an agreement to support pure mathematics which had no identifiable use" [9].

Rees' efforts at the ONR were widely appreciated in the research community and she received many honors. In 1983, she received the Public Welfare Medal of the National Academy of Sciences for "eminence in the application of science to the public welfare." But Rees felt the honors she received from mathematical organizations meant the most to her. "Among the many honors that I have received, I cherish most the three I received from mathematical groups" [11, p. 17]. These awards included resolutions in her honor by the American Mathematical Society and the Institute of Mathematical Statistics. In 1962, Rees received the first Award for Distinguished Service to Mathematics from the Mathematical Association of America [12].

14.3.3 Returning to Academia, 1953–1972

With the founding of the National Science Foundation (NSF) in 1950, Rees knew she would not stay at ONR. She had several offers, but for the fourth time, Rees returned to her roots and her alma mater, which became part of the City University of New York (CUNY) when that system was created in 1961. This time she would stay in the CUNY system until her retirement in 1972 as Professor Emeritus and President of the Graduate School and University Center (GSUC) of CUNY. "I spent 7 years in Washington until, in 1953, I left to return to Hunter as Dean. The experience in Washington [at ONR] had given me administrative and academic sophistication that would have been hard to get elsewhere. [. . .] My course was set. I was committed to administration, not research, but administration with a heavy orientation toward science" [11, p. 17].

Upon her return to Hunter College in 1953 as a Professor of Mathematics, she was also appointed Dean of the Faculty. When the various New York City colleges were brought together under one administration as CUNY in 1961, she was appointed the first Dean of Graduate Studies. As Graduate Dean, she worked to establish a separate graduate school within the CUNY system. When that school, the GSUC, was inaugurated in 1968, Rees was named Provost.[3] The following year, she became the first President of GSUC. Until her retirement in 1972, Rees spent much of her time building GSUC, always looking to the future and not the graduate models of the past. As she said, "[t]he building of a graduate school that called upon and stimulated the growth of the scholarly and physical resources of so many established liberal arts colleges and that achieved acknowledged first-class graduate work in a brief period of time required the combining of traditional elements of academic structure with often difficult innovations" [11, p. 18]. But years of work on hard problems in the face of entrenched norms had served Rees well. She was clearly up to the task and achieved success with many goals for the new graduate school.

14.3.4 Advocating for Women in Mathematics

Rees' efforts to bring more women into advanced study in all fields were significant. As more and more women, at all stages in their lives, started attending college and graduate school, Rees clearly saw the need for flexibility. Modern graduate students and non-traditional students, especially females, could not be expected to be solely students. They were employees, spouses, and parents. Rees strove to build a program at CUNY that nurtured instead of alienated these new types of students, and advocated for similar programs across the country. In "The Dilemma that Faces Us," a 1965 article about the future of graduate education, Rees spoke of the graduate program at CUNY and its early successes with female graduate students:

[3]The library of GSUC at CUNY is now named after Rees.

> [O]urs is proving an ideal university to draw into advanced graduate work the most obvious source of unused talent in a society that desperately needs additional numbers of persons with training through the doctorate, namely women. [. . .] We have welcomed qualified women who have applied even to the extent of considering the need for a babysitter a proper reason for providing financial assistance [7].

The number of women receiving advanced degrees has continued to rise nationally since then. But Rees' words are still relevant, perhaps even more so today, as we struggle to bring other underrepresented groups into advanced work in mathematics and science. Rees' support of the education of women is apparent in a letter she wrote to the AWM in 1990 to accompany her donation to the Schafer Prize fund, "I was . . . thrilled at the clear indications that we shall be producing truly distinguished women mathematicians in the immediate future who will carry on the trend that is well on its way" [6, p. 868].

From the 1950s through the 1980s, Rees was also heavily involved in educational reform at all levels, including on a national scale. She took on important roles on numerous committees, including service as a member of the advisory board of the influential School Mathematics Study Group in the early 1960s. In 1970, she became the Chairman of the Council of Graduate Schools of the United States. Perhaps most impressive for a woman in the mid-twentieth century were two particular events. In 1964, President Johnson appointed Rees to the National Science Board of the NSF. Prior to this, she had been involved with the NSF in several advisory roles from its inception, and served on the Advisory Panel for Mathematics from 1955 to 1958. Rees served on the National Science Board until 1970 (Figure 14.2).

Fig. 14.2 Mina Rees accepts her appointment to the National Science Board of the National Science Foundation from President Lyndon B. Johnson and Claudia "Lady Bird" Johnson in 1965. Photo Courtesy of the Graduate School and University Center Archives, CUNY.

In 1971, Rees became the first female president of the American Association for the Advancement of Science (AAAS). The AAAS was founded in 1848 and past presidents included Benjamin Peirce (1852), Frederic Ward Putnam (1898), Albert Abraham Michelson (1910), E. H. Moore (1921), George David Birkhoff (1937), and Warren Weaver (1954). Since Rees, roughly half the AAAS presidents have been women [1].

14.4 Conclusion

Rees maintained her connections with other mathematicians her whole life. But her friendship with Richard Courant, who died in 1972, was especially close. She was viewed as a personable and warm administrator and leader, but as a woman in a male-dominated field, she felt that she had to remain fairly aloof, and rarely shared her personal life. Since she did not often share her personal thoughts, it is worthwhile listening to them, both for their insights into mathematics and research in the middle of the twentieth century, and for their implications for today. Rees continued her work at the national and local levels long after her official retirement, never really slowing down her dedication to education, to scientific research, and to her hometown of New York City. She died in Manhattan in 1997.

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Chapter 15
An Ambition to Give: Gertrude Cox's Institution Building at Home and Abroad

Patti W. Hunter

Abstract Gertrude Cox (1900–1978), first chair of North Carolina State University's Department of Experimental Statistics, worked as a consultant for the Ford Foundation to Cairo University's Institute of Statistical Studies and Researches in 1964. This chapter will analyze the developments that led her there as well as her contribution to that project in order to uncover some unexplored ground in the history of women in American science and in the history of statistics. It will document Cox's commitment to serving her professional community and highlight some qualities of Cox's approach to her work that enabled her to accomplish what other colleagues tried unsuccessfully to do.

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Keywords Gertrude Cox • Ford Foundation • Statistics education • Egypt

15.1 Introduction

In April, 1966, Gertrude Cox, the retired director of the University of North Carolina's Institute of Statistics, gave a talk to her local chapter of the American Statistical Association (ASA), entitled, "Education in Statistics." Cox had spent the 1964–65 academic year living in Cairo, Egypt, serving as a consultant for the Ford Foundation to Cairo University's Institute of Statistical Studies and Researches. At this ASA banquet, Cox described some of her experiences in Egypt, reflecting on what she had learned about the needs of the statistics programs in the country and comparing them to those in the United States. Cox included some comments about the historical development of the discipline in these remarks. "The status of statistics in the rapidly developing countries," she observed, "is not too different from what my generation experienced in the nineteen twenties" in the United States [5].

P.W. Hunter (✉)
Westmont College, Santa Barbara, CA, USA
e-mail: phunter@westmont.edu

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Cox, born in 1900, was a member of the generation that saw the establishment of statistics as a discipline in the United States. She received her training and began her career as a statistician during the 1930s and 1940s—the American statistical community's formative years—just as such training and careers were becoming possible. As the first recipient of a degree in statistics from Iowa State College, as the first head of the first university department of statistics in the United States (North Carolina State College), and as an active leader of professional statistics organizations throughout the world, Gertrude Cox's life reveals much about the early years of statistics in the United States.

Here, however, her experiences and contributions will be analyzed not in the context of the birth of the American statistics community, but rather as a case study documenting the unusual success of a woman scientist whose career exhibited some of the typical challenges faced by American women in science during the twentieth century. In her two volumes of *Women Scientists in America,* Margaret W. Rossiter documents the processes that gave women places in the scientific communities of the United States from the nineteenth century to the equal rights legislation of the early 1970s [39, 40]. Cox's professional activities (mentioned in [40]) spanned the two periods covered by Rossiter's books. Her education and early career before 1940 exemplify the limitations and barriers women confronted in academic science, as well as some of their responses. Cox's success building statistics research and teaching programs at universities in North Carolina and her role in promoting such programs abroad make her "exceptional" after 1940. This case study will document Cox's commitment to serving her professional community and the contribution that commitment made to her success in Egypt. In particular, it will uncover some of the particular qualities of Cox's approach to her work that enabled her to accomplish what her male colleagues were less able to do.

Gertrude Cox's efforts to promote university statistics training abroad, and in particular, her trip to Egypt in 1964 highlight issues in a range of other areas as well, including the internationalization of the statistics profession, the systems of patronage available to scientists in the second half of the twentieth century, and the nature and practice of the discipline of statistics during this period. An expanded version of this paper explores those other themes [30]. Additionally, in previous work I have described the process by which mathematical statisticians in the US created a professional community for themselves, distinguishing their interests in theory from the applications of statistics that were tools for, among others, social scientists in the early twentieth century [28, 29]. The emergence of mathematical statistics (both as a scientific discipline and a profession) was only one aspect of the history of statistics in the twentieth century. As researchers in agriculture, medicine, economics, sociology, and engineering—to name just a few disciplines—learned to use and develop the increasingly sophisticated tools of statistics, professional communities supporting these diverse interests sprang up. They published research journals, created academic societies, and carved out their own niches in government, industry, and academia. The story of Gertrude Cox's career, and her work abroad help illuminate those broader developments.

15.2 Gertrude M. Cox: Education and Career

Gertrude Cox was born in 1900 in Dayton, Iowa and attended Iowa State College, receiving a bachelor's degree in mathematics in 1929 and a master's degree in statistics in 1931.[1] After two years studying psychology at the University of California, Berkeley, Cox returned to Iowa State as a research assistant to George Snedecor, the director of the college's statistics program. She became a Research Assistant Professor in 1939 [19–21, 33]. As a researcher and teacher in the Statistical Laboratory, Cox worked in the field of experimental design. She later co-authored a textbook on the subject with William G. Cochran, who joined the statistics staff at Iowa State in 1939 and followed Cox to North Carolina in 1946 [23].[2]

Cox went to North Carolina State College in 1940 when the institution established its Department of Experimental Statistics. The department, with Cox as its first chair, provided consulting for researchers and service courses for students in the School of Agriculture, in addition to granting degrees [37]. As demand for the consulting and computing services grew, the department became part of a college-wide Institute of Statistics in 1944, with Cox as its director. Two years later, Cox succeeded in having the Institute made a division of the state's university system so that it served the three universities in the system.[3] She also secured funds to start a Department of Mathematical Statistics at the University of North Carolina, Chapel Hill (UNC). As director of the Institute, Cox hired Harold Hotelling to chair the Department of Mathematical Statistics. Hotelling, a prominent member of the American mathematical statistics community who had been teaching statistics in the economics department at Columbia University, served as an associate director of the Institute under Cox, along with William G. Cochran, who left Iowa State to chair the Department of Experimental Statistics at North Carolina State [37, p. 176].[4]

Cox remained in her position as director of the Institute of Statistics until 1960 when she became the first director of the Statistics Research Division of the newly created Research Triangle Institute, a non-profit organization providing contract research to government and industry [31]. In 1964, she left this position to begin her consulting trip to Egypt. That trip did not mark the beginning of Cox's international work in statistics nor her first contribution outside of North

[1]The mathematics department granted graduate degrees in statistics until Iowa State established its department of statistics in 1947. The first Ph.D. in statistics at Iowa State was earned by Holly C. Fryer in 1940. Cox received an honorary D.Sc. from Iowa State in 1958.

[2]On Cochran, see the brief biography and discussions of his contributions to statistics in [38].

[3]In 1931, the state of North Carolina united three of its institutions of higher education—the University of North Carolina in Chapel Hill, North Carolina State College of Agriculture and Engineering in Raleigh, and the North Carolina College for Women in Greensboro—into a single system, known then as the University of North Carolina. For the details of the events surrounding this unification, consult [45]. Other state universities joined the system over the next forty years, including the state's Historically Black Colleges and Universities.

[4]For biographical information on Hotelling, see [34, 35].

Carolina to the promotion of the statistics profession. Indeed, her role in the statistics community had extended beyond the borders of North Carolina and the United States from the early years of her career.

She was an active member of both the American Statistical Association (ASA) and the Institute of Mathematical Statistics (IMS). Both organizations recognized the importance of her contributions to the statistics community and elected her a fellow in 1944. Cox served on the governing boards of the IMS and the ASA in the late 1940s and was president of the ASA in 1956. She edited the international journal, *Biometrics,* from 1945 to 1955, helping to launch the Biometric Society in 1947.

Cox's prominence as a scientist and administrator was an unusual accomplishment for a woman in the United States during the decades following World War II. The field of statistics, like many other sciences, flourished and expanded as funding increased in the postwar era, and as historian Margaret Rossiter has pointed out,

> [Cox] got a good start during World War II and just kept on growing and building as her field broadened and the federal and other funding blossomed. She not only managed to ride the wave of Big Science in the 1950s and 1960s but to be enough ahead of it to help shape the form it took and the impact it had on her university, field, and region [40, pp. 203–204].

Although Cox's professional success from the time she moved to North Carolina State was unusual, the early stage of her career reflects many of the issues facing women in academia (and in science in particular) in the first half of the twentieth century.[5] She entered college at age 25, after a brief pursuit of church-based social work. Although she taught a graduate course in experimental design at Iowa State from 1934 to 1939 and published seven papers between 1931 and 1939, she did not receive her promotion from Research Assistant to Research Assistant Professor until 1939.

This appointment—still not a regular faculty position in the college—came a year after a joint project with the US Department of Agriculture provided funds for the expansion of the Statistical Laboratory and the hiring of two new staff members, Charles P. Winsor, who came from Harvard with a Ph.D. in physiology, and William Cochran, who had spent the previous four years working at Rothamsted Experimental Station in England with Frank Yates and who had master's degrees from Glasgow University and Cambridge [18]. So, although arguably as qualified as others hired at the time, Cox was passed over for advancement. For the first nine years of her career, she fell among the women scientists Rossiter describes as "lost in labyrinthine passages that worked in a variety of ways to keep them in low ranks, pay them lower salaries, and direct them to adjunct positions as research associates" [39, p. 216]

Rossiter acknowledges that while "it has been possible to document this phenomenon of discrimination ... it is more difficult to penetrate the mentality that

[5] Perhaps surprisingly, neither her own papers nor the writings of others who mention Cox seem to raise gender issues explicitly or to go beyond brief acknowledgment of the fact that her accomplishments were unusual for a woman.

perpetrated it." She suggests that intense competition for prestige among men in academia and the precarious "economic and social position of the professoriate" in the 1920s and 1930s often prevented women from getting equitable treatment (*ibid.*). What limited Cox in particular during that first decade of her career is difficult to document. Until the Laboratory's expansion in 1938, she was one of three staff members working under George Snedecor. He had been her graduate advisor, and she coauthored papers with him, did some of the statistical analysis for his agricultural research, and supervised the staff performing the calculations needed in the research [43, pp. 699–700], [44].[6] In Snedecor, Cox had a mentor and a sort of benefactor. She may also have experienced what Rossiter describes as one of the "pitfalls to this kind of personal patronage." Such support sometimes "led to the unfortunate assumption (for female but apparently not for male protégés) that the young woman was merely helping the professor with his research rather than doing her own work" [39, p. 186].

Whether Cox felt trapped by Snedecor's sponsorship or deprived of proper credit for her contributions is not clear. In the obituary of Snedecor that she coauthored, Cox expresses "her sincere personal appreciation of his great intelligence, patient instruction, high standards of excellence, wise counsel, and friendship" [24, p. 266]. Yet she also quotes him announcing (inexplicably, according to Cox), "All smart women get married," when she reported some concerns she had about the computing work she was supervising [24, p. 280]. Cox described Snedecor as "a gallant southern gentleman, popular with the women and favored [*sic*] pretty girls in his classes." She quotes Cochran's remark that "If I wanted to speak to George [Snedecor] at a large social gathering, my strategy was to look for the three prettiest girls at the affair. George would be found sitting talking to one of them, or perhaps to all three" [24, p. 287].

Snedecor may have simply been blind to the possibility that a woman could advance professionally in what was then very much a man's world. When he was asked to recommend someone to head the Department of Experimental Statistics being created at North Carolina State College, "he listed the names of five young men that he recommended, then he half-heartedly added, 'If you would consider a woman, I know of no one better qualified than Gertrude M. Cox'" [24, p. 284].[7]

[6]Cox's role in supervising the computing services points to another issue in the history of women in science with connections to the history of statistics. Before the widespread use of electronic computers in statistical research, the job of performing the long calculations needed in that research was just the sort of tedious, anonymous "women's work" that had created jobs for women in astronomy in the late 19th and early 20th centuries. See [39, pp. 53–55]. Rossiter discusses the place of women in computer science in the 1960s, but a detailed analysis of women's participation in the (human) computing side of statistics is needed. For some information on the history of human computers, see [27].

[7]It is not clear if Snedecor meant that Cox was the most qualified among all statisticians he would recommend or only among the women. Moreover, these may not be his precise words (see footnote below).

According to one account, he made this addition only after Cox asked him why the list did not include her name [20, p. 4].[8]

If her assertiveness resulted in her recommendation to NC State, her talents, energy, and personality made her successful there and resulted in the creation of one of the most highly regarded university statistics programs in the United States. The experience and prestige she earned through this accomplishment gave her opportunities to advise and encourage other university administrators and statisticians in the United States and abroad as they sought ways to develop statistics research and education programs in their own institutions.

Cox's trips abroad often coincided with her attendance at the biennial meetings of the International Statistical Institute (ISI). Founded in 1885, the Institute consisted of a limited number of elected members (150 in 1885)—government officials responsible for their nations' data-collection and academic researchers renowned for their contributions to statistics. Cox was elected a member of the ISI in 1948. At the time, she was one of twenty American members (out of a total of 200), and the only woman.[9] She served as the organization's treasurer from 1955 to 1962, and then as the chair of the ISI's Education Committee. Through her work for the ISI, and particularly for the Education Committee, Cox developed her interest in Cairo University's Institute of Statistical Studies and Researches, and the personal and professional contacts that led to her visit to Cairo in 1964. In order to trace those developments, we will consider some details of the ISI's history and of Cox's involvement.

15.3 The ISI Education Committee: An International Agenda

When it was founded in the late nineteenth century, the ISI had focused on improving and standardizing governments' methods of collecting and organizing demographic and economic data. By the time Cox was elected in 1948, two major alterations to the landscape in which the ISI operated would affect Cox's participation in the coming decades. First, changes in the discipline of statistics, both in the body of knowledge and in its use, added to the complexity of the ISI's work by the middle of the twentieth century. Statistics to the nineteenth-century founders were numbers—data about populations, economic conditions, and diseases. Statisticians concerned themselves with collecting that data, with

[8]Here, Snedecor's letter is quoted as "Of course if you would consider a woman for this position I would recommend Gertrude Cox of my staff."

[9]Note that [9] puts the number of American (US) members at 20, with Cox as the only woman, while [36] puts the number of American members (representing an unspecified five countries) in 1948 at 38, though clearly "American" here refers to the broader continent rather than to the United States.

organizing them for presentation, and with drawing conclusions about the problems and conditions illuminated by the data. Those tasks still formed part of the work of the statistician in the middle of the twentieth century, but the process of collecting data and drawing conclusions had been dramatically transformed by the work on distribution theory, sampling, estimation, and hypothesis tests pioneered by Karl Pearson, R. A. Fisher, Jerzy Neyman, and Egon S. Pearson—to name only the most prominent of the earliest contributors.

Statisticians were no longer simply government officials who collected data. They were biologists who designed experiments on varieties of corn, industrial engineers who controlled the quality of mass-manufactured goods, social scientists who surveyed random samples of people in order to make inferences about larger populations, all kinds of scientists who needed probability-based models of the phenomena they studied, and mathematicians who created those models and studied their abstract properties. In addition to having a variety of research interests, many of these scientists—unlike the government statisticians of previous decades—tended to depend on academic institutions for employment, and on professional scientific societies for the dissemination of their ideas. The ISI served a much more diverse constituency in 1948 than it had in 1885.

The second major change to the landscape diversified the ISI's work in a different way. The end of World War II saw the creation of the United Nations, and with it more explicit efforts to promote international cooperation in a range of areas, as well as more funding to support those efforts. The main tasks of the ISI—coordinating the collection of demographic and economic data among various nations—became the domain of the United Nations Statistical Commission. In response, the ISI revised its governing statutes in 1948 in order to carve out a new niche for the organization. In particular, it shifted the focus of its work to two new areas: bringing together statisticians from different statistical societies and encouraging statistical research. There is some evidence to suggest that Cox had a hand in encouraging the ISI to move in this new direction, and over the next decade, Cox became an active participant in the Institute, helping to coordinate its work and pursuing funding for its activities. In particular, she joined the ISI's Education Committee, eventually taking on the role of chair.[10]

The committee's central work focused on promoting education and training of statisticians in developing countries to contribute to economic advancement. In the early 1950s, as a result of the collaboration between the ISI and the UN, the ISI Education Committee helped establish and support statistics training centers in India and Lebanon. These centers provided training to government workers in collecting and analyzing data and received financial support from the United Nations Educational, Scientific and Cultural Organization (UNESCO), the governments of India and Lebanon, and the Ford Foundation [25, p. 328], [26, p. 92]. After setting

[10]The minutes of the Education Committee's meetings list Cox as attending as early as 1957. See [13].

up these training centers, the Education Committee decided "to explore the needs and possibilities for a regional statistical education centre in tropical Africa" [14].

This move came in response to a suggestion from the committee's UNESCO representative, B. A. Liu, who reported at the 1958 committee meeting that the UN Economic Commission for Africa had recently been established. The Education committee's exploration went slowly, and two years later, frustrated with this slow pace, Liu wrote to Cox in December, 1960, of UNESCO's plans to include statistics training for African civil servants in its upcoming annual budget. "You know I have tried to get the ISI Education Committee to take a special interest in promoting statistical education in Africa," he reminded her, "but events are moving faster in Africa than the ISI Committee can keep abreast of" (Liu to Cox, 28 December 1960, in [8]). Liu, who had known Cox at least since 1955, had written to her because of his "great respect for [her] broad perspectives and sound judgment," hoping that some definite plan would emerge from the next committee meeting, to be held in Paris in August, 1961 (*ibid.*).[11]

Cox shared Liu's frustration, and by the time she became the Committee's chairman in 1962, she was steering it toward work in Africa. At the Paris meeting, the committee had discussed the potential to create a training center at the newly established University of East Africa (consisting of Makerere College in Uganda, Royal College of Nairobi, and University College, Tanganyika) or at the University College of Rhodesia and Nyasaland.[12] Cox also thought that "there should be some way to use the facilities and personnel at the three universities in the Union of South Africa" (Cox to H. L. Manning, 10 January 1962, in [8]).

In the latter case, she expressed some concerns about racial issues and whether these institutions admitted African students along with Europeans. In a letter to a former student, H. L. Manning, who was then doing agricultural research in Uganda, she confessed, "I should understand more about the race problems in Africa." She also worried about a narrowness of focus in the proposal from Makerere College. "As you know," she wrote to Manning, "I would strongly urge a well-rounded program including basic methods and theory. The statistics needed in economics and for official statistics should be a part of the statistics degree program, but no greater a part than experimental designs and analysis of variance tools" (*ibid.*).

In a letter to Bart Lunenberg, director of the ISI's permanent office in The Hague, she raised similar issues about the proposal from the University College of Rhodesia and Nyasaland. "I believe there is some question yet about whether their University is really interested in the education of Africans," she told Lunenberg. Moreover, she thought that the proposal, like that for Makerere College, put too much emphasis on economics training and the collection of official statistics. As

[11]Cox and Liu both appear on the list of people present at the 1955 ISI Education Committee meeting; see [12].

[12]Tanganyika is now known as Tanzania. The Federation of Rhodesia and Nyasaland, in existence from 1953 to 1963, was comprised of the former British protectorates of Northern Rhodesia, Southern Rhodesia and Nyasaland, which eventually became Zambia, Zimbabwe, and Malawi, respectively.

she put it, "especially in Africa one must plan not only for better official statistics but for better experimental work in agriculture, medicine and industry" (Cox to Lunenberg, 8 January 1962, in [8]).

Both the concerns about narrowness of curriculum and the racial issues highlight complications created by the move toward independence in these countries during the 1960s. They suggest that investigations of the impact of colonialism on education would provide important perspectives for the study of the internationalization of statistics in this period (see [32]). The institutions Cox was investigating were either newly created or in the process of establishing their autonomy from parent institutions in England. The existing curricula were based on a system that gave degree-granting authority to the parent institutions. Cox's concerns about the scope and focus of university statistics programs in Africa also reflected the changes that had occurred to the profession's landscape over the previous half century. An emphasis on economic and official statistics was narrow and outdated by this time, while statistical experiments and probability-based methods of analyzing data had become commonplace in scientific research in the United States and other developed countries.

The promotion in African institutions of these newer aspects of the discipline would not only meet needs but ought to attract funding. "I think some of the agricultural and industrial interests in Rhodesia would help finance a program in statistics training" (Cox to Lunenberg, 8 January 1962, in [8]). Cox also looked to UNESCO and US philanthropies as sources of funding. She intended to pursue these sources, assuring Lunenberg that "As soon as possible, I will visit the Foundation folks in New York for exploratory purposes" (*ibid.*).

15.4 The Ford Foundation, Overseas Development, and University Statistics Training

In particular, Cox had plans to meet with officials from the Ford Foundation. Founded in 1936 by Henry Ford and his son Edsel, the Ford Foundation began as a family philanthropy, making grants in the Fords' home state of Michigan. After the deaths of Edsel Ford in 1943 and Henry Ford in 1947, the Foundation reorganized as a national philanthropy, independent of Ford family control. At the same time, it broadened the scope of its grant-making.

By 1962, when Cox approached the Foundation about supporting statistics training in Africa, Ford had spent $152.6 million in forty countries in Asia, Africa, the Near East, Latin America, and the Caribbean. Describing this grant making, a 1962 Ford report categorized the assistance as "largely in support of education, training, and research institutions and activities essential to the recipient countries' own programs of social, economic, and educational advancement" [22, p. 8]. As it looked to the decade ahead, this 1962 report promised that the Foundation would "continue to assist efforts of these countries to establish or improve their educational institutions, programs, and practices as a means of producing the trained leaders, skilled persons, and enlightened citizens essential to their national development" [22, p. 12]. The Foundation also planned to contribute to rural development overseas, giving support "to institutions and programs to increase agricultural production, improve rural life, and raise nutritional levels" [22, p. 13]. Cox had long believed that statistical methods could play an important role in such work and her efforts on behalf of statistics programs in Africa simply continued a pattern of advocacy established early in her career. These efforts also illustrate Cox's knowledge of statistical programs in developing countries and the high regard in which she was held by a number of foundation and university officials throughout the world.

On January 17, 1962, fulfilling her promise to Lunenberg to "visit the Foundation folks," Cox had what she described as a "most profitable session" with F. Champion Ward, head of the Ford Foundation's Near East and Africa Program. As she wrote to William Leonard, a statistician working in the UN's Economic Commission for Africa, she had briefed Ward on UNESCO and ISI interest in promoting statistics training in Africa.[13] Ward indicated that the Foundation was considering supporting the overall development of the University of East Africa. "It became increasingly evident," she told Leonard, "that our chances of getting funds for statistical training at the University of East Africa were quite good" (Cox to Leonard, 29 January 1962, in [8]).

To some extent, Cox's confidence derived from an ability to read between the lines. As she would later tell a correspondent, foundation officials tended to talk "in general terms for they are skillful at making no commitments" (Cox to C. P. Welter, 9 July 1963, in [8]). In the meeting, she and Ward discussed the University of East Africa, as well as the proposal and possible budget for the University College of Rhodesia and Nyasaland. In the course of the conversation, Cox "realized that Dr. Ward had reservations" about the latter institution. While "[i]t was difficult to get much response of a constructive nature," Ward finally expressed his doubts about whether Africans would choose to attend the university. Then, just as the meeting ended, Ward mentioned the University College of Ibadan in Nigeria, going on "enthusiastically about the College," its medical school, and its research in agriculture and economics. Apparently, "[h]e felt that the political and racial problems would be less there than at most any other place in Africa." As Cox reported to Leonard, "This came as a surprise move to me. Dr. Ward had given me almost two hours of his time and it was near closing time." She told Ward that she would investigate the Nigerian college's potential for providing statistics training (Cox to Leonard, 29 January 1962, in [8]).[14]

[13] On Leonard, see [41].

[14] Cox's work with the ISI Education Committee did not ultimately lead to any connections with the Nigerian institution.

Cox continued to make inquiries into possibilities for statistics training in Africa through the first seven months of 1962, establishing contacts among university professors and administrators, government officials, and people connected with United Nations and United States agencies. In August, she spent a week in the region to get a first-hand sense of the possibilities for establishing training programs. Spending two days in Salisbury (now Harare), she provided some advice on the University College of Rhodesia and Nyasaland's proposal for an Institute of Statistics. The university submitted this proposal in November, 1962, to the Ford Foundation, which turned it down [1].[15]

Meanwhile, the Foundation representative in Cairo, John Hilliard, was preparing a proposal to fund a statistics program in Egypt. A week after Cox first met with Champion Ward in January, 1962, Hilliard wrote to Ward that he had been "approached by Dr. Hassan Hussein, Under Secretary of State for Statistics . . . regarding Foundation support for establishment of a National Institute of Statistics." Hilliard explained that "Hussein is looked upon as the legitimate dean" of the group of "a few highly qualified people in the various statistical specializations in Egypt." In the last few years, accurate statistical information had become "a critical factor in national planning and in monitoring the execution of the plan for national development," and Hilliard described an emerging "recognition of the need for a competent central statistical agency" that could coordinate the country's statistical training and research (Hilliard to Ward, 25 January 1962 in [16]).

Within two months of Cox's meeting with Ward and Hilliard's letter to him, another Ford staff member in the Near East and Africa division, David MacEachron, was thanking Cox for her "generous offer to help find suitable candidates for the assignment in the U.A.R. [Egypt]" (MacEachron to Cox, 22 March 1962, in [8]).[16] Plans were underway for the Foundation to send what it called "program specialists," or visiting consultants, to the Egyptian statistics training center, "when

[15]Cox presented this report of her work on establishing statistical education centers in Africa to the ISI Education Committee at its 1963 meeting in Ottawa. She must have learned of the Ford Foundation rejection of the University College proposal just before the meeting, as her handwritten notation "Turned down" appears in the margin by the typed statement, "I have no report on the status of this proposal." Since the Federation of Rhodesia and Nyasaland broke up in December 1963 and the territories of Northern Rhodesia and Nyasaland became the independent nations of Zambia and Malawi the following year, it seems likely that the uncertain political situation in the region played a role in the Ford Foundation's rejection of the grant proposal.

[16]This letter is also in [16]. Neither archive collection contains documents explaining when Cox offered to help with this project. It is possible that she discussed the issue with Ward at their January meeting, or that the offer emerged in subsequent phone conversations. She had certainly made a favorable impression at her meeting with Ward. As MacEachron reported to Hilliard, "Champ is very impressed with Dr. Cox and thinks that she has about as thorough a knowledge in the statistical field as anybody around" (MacEachron to Hilliard, 6 April 1962 in [16]). Note that Syria and Egypt united in 1958 to form the United Arab Republic (UAR). Syria seceded from the union in 1961, but Egypt continued to be known as the UAR until 1971.

it is formally established," and to provide fellowships for Egyptian students to study abroad. MacEachron hoped that Cox could suggest names of statisticians who would serve as consultants.

He acknowledged that Cox knew "the situation in Cairo so much more thoroughly than I" (*ibid.*), and indeed, as Cox replied in her letter, the University of North Carolina had trained "quite a few" Egyptian students who now worked in government, universities, and research programs in Egypt. Cox was acquainted with Husein and Abdul Moneim El Shafei, another Egyptian official with whom the Ford Foundation was negotiating its grant (*ibid.*).[17]

At its 1961 Paris meeting—the same meeting that initiated Cox's work in Africa—the ISI Education Committee had helped draft a curriculum "for a M.S. in statistics [at Cairo University] which would prepare the better students who desired advanced training to enter Ph.D. programs in statistics in the United States." As she put it in her letter to MacEachron, "We are exceedingly interested in doing all we can to help them with the development of the National Institute of Statistics" (Cox to MacEachron, 2 April 1962, in [8]). The Ford Foundation's interest in the program persisted, and in January, 1963, Hilliard sent a proposal to Ward, requesting support for Cairo University's Institute of Statistical Studies and Researches (ISSR).[18]

In the early stages of preparation of the ISSR grant, Ford officials turned to Cox for some of the advice and consulting the ISSR needed to get established. Cox began a search for a visiting statistician to advise the ISSR, simply extending her recruiting work for the ISI Education Committee as she assisted the Ford Foundation on an informal basis. In September, 1963, the Foundation formalized her advising role with a contract that would pay her for the recruiting work (Harvey Hall to Cox, 20 September 1963, in [8]).[19] Cox described this appointment to a colleague at the Research Triangle Institute as giving "status to the work I have been doing as part of my professional responsibility for the Education Committee of the International Statistical Institute" (Cox to George Herbert, 3 October 1963, in [8]).

The people she suggested had a range of experience and prestige. Some were recent graduates of the programs in North Carolina; some served on the faculty in those programs. One recent graduate, William Mallios, had completed a Ph.D. in experimental statistics at NC State in 1962 and had been working for a management

[17]Except in quotes of others, my spellings of names reflect their appearance in letters written by the people themselves. Husein is a case in point: Hilliard spelled his name incorrectly as "Hussein" in the letter cited above.

[18]Note that Ford initially considered funding the creation of a government-sponsored statistics training program. In the end, in part because of Cox's involvement, the grant went to Cairo University's ISSR. This division of the university was not new, but had operated on a much smaller scale before Ford's involvement and did not enroll students between 1959 and 1962, so Institute officials as well as Cox and other Foundation staff typically thought of this Ford project as launching the Institute.

[19]The contract provided for a fee of $90 per day, any required air travel, and reimbursement of expenses. It covered 30 days of work over a period of one year (Robert Schmid to Cox, 30 September 1963, in [8]).

consulting firm (Mallios to Harvey Hall, 29 May 1963 in [17]). Cox urged Husein to consider hiring Mallios, believing that he had "the capabilities necessary to direct masters thesis work," and the ability to provide consulting services for researchers in other fields, though she admitted that "his name does not carry the prestige value" Husein wanted (Cox to Husein, 3 October 1963, in [8]). She proposed that Mallios begin immediately, while they continued to recruit a more senior statistician.

In his reply, Husein indicated that he wanted to hold out for a more experienced program specialist. Taking a point of view that Cox would later criticize as a hindrance to the ISSR's development, he downplayed the importance of bringing in someone with consulting abilities and expressed more interest in having someone "with a strong theoretical backgrou[n]d who can handle some masters and doctors [sic] degree theses ... Consul[t]ation is also useful but can perhaps come later on. The main thing for him is to be able to do research with graduates" (Husein to Cox, 19 September 1963, in [8]).[20]

Cox continued recruiting statisticians for the next several months, and by December 31, 1963, Cox reported to Husein that she had tentative agreements from three statisticians to serve as visiting faculty at the ISSR in the coming years: Carl Marshall, Robert Hader, and Paul S. Anderson, Jr. Marshall, who would go to Cairo in 1965, helped create the statistics program at Oklahoma State University and had a Ph.D. from Iowa State University. Hader, tentatively available in 1966 or 1967, had received a Ph.D. from NC State's Department of Experimental Statistics in 1949, and subsequently joined its faculty. Paul Anderson taught in the Department of Epidemiology and Public Health at Yale and was interested in going to Cairo in 1968.[21]

The ISSR and Ford had hoped to hire a program specialist for the 1964–65 academic year and Cox told Husein in her December letter that she planned to meet with Harvey Hall at the Foundation on January 10. "If he agrees with my suggestion," she wrote, "we will propose to you the name of a person for the Fall of 1964" (Cox to Husein, 31 December 1963, in [8]). The proposal met with approval. The ISSR would have its mature, experienced statistician with prestige value. As James Lipscomb wrote to a colleague at the Foundation in February, "Dr. Hussein was delighted to have word that Dr. Cox might be available to come and work with ISSR during the 1964–65 academic year" (Lipscomb to Donald Kingsley, 13 February 1964 in [17]).[22]

[20]Clearly, Husein is responding in this letter to Cox's letter of 3 October, so it seems that the date on the letter must be incorrect.

[21]Marshall had been at Oklahoma State University since 1931. He earned his Ph.D. in 1956. His other experience abroad included work for the US State Department in 1947, overseeing the Greek election, and statistical consulting for a US-sponsored program in Ethiopia in 1953 [11]. Ultimately, Hader and Anderson did not go to Cairo.

[22]Kingsley was director of Ford's Middle East and Africa office in 1964.

15.5 Cox's Work for the ISSR

Cox landed in Cairo on the fifth of September with little more than a vague sense of the Institute's expectations of her and of the role she could play in furthering the goals of its staff. By the end of October, when she sent out her first "Diary Letter" from Egypt to friends and colleagues in the States, Cox had established something of a routine. She was teaching a weekly class for research workers and a graduate course of nine students twice a week, with plans being made for an elementary course for diploma students. Her busy consulting schedule included agricultural studies, research on infant mortality and family planning, and work for the university's School of Pharmacology (Cox, Diary Letter No. 3, 30 October 1964, in [8]).

When possible, she had her graduate students participate in the analysis of the data obtained in her consulting work (ibid.). She found them lacking experience with the applications of the statistical methods they had learned: "They know about the statistical tools but they do not know much about when and how to use them." Assessing the local faculty, she observed that "the teachers of statistics have done no research or consulting work except maybe in economics," so that their attempts to analyze research data were often done "textbook style" (Cox to C. and E. Cox, 2 November 1964 in [10]).

By the spring, Cox was still "doing a great deal of consulting," along with supervising the research of five graduate students at the Institute and teaching four classes, including a weekly course at the university in Alexandria, a two-hour train ride from Cairo (Cox to C. and E. Cox, 29 May 1965, in [10]). Outside her course work, she gave lectures on the need for statistical methods in research to others in the university and traveled to Beirut to visit the ISI's International Statistical Education Center, giving several lectures there [2, 3].

When her time in Egypt approached its end, Cox puzzled over how organizations such as the ISI and the Ford Foundation could continue promoting statistics education in Egypt and in other developing countries. Eight months into her work at the ISSR, she wrote to the director of the ISI, Bart Lunenberg, that her "experiences . . . here have been a real education to me regarding how the education in stat[istics] should be developed in these countries." Still, she admitted, "I am more confused than ever to know how we can assist these developing countries with their statistical education problems" (Cox to Lunenberg, 19 April 1964, in [8]).

While she may have been confused about the most effective way to assist university statistics programs in Egypt and elsewhere, Cox had definite ideas about what those programs needed. She spelled out these ideas in her report to the ISSR and the Ford Foundation at the conclusion of her stay. First, she asserted that the effective training of Egyptian statisticians would continue to require input from statisticians abroad. "It seems desirable," she wrote in her report, "to keep on the ISSR program one or two visiting statisticians who have had extensive experience consulting, directing research, supervising theses and teaching" [4].

In addition to suggesting that the ISSR bring in visiting statisticians, Cox noted that for at least several more years, Egyptian students would need to go abroad themselves for advanced training. She had recommended to Hasan Husein, the director of the ISSR, that her five graduate students from the Institute be sent to the United States to complete Ph.D.s in statistics. Shortly before her departure from Cairo, Cox noted in a letter to her brother that "two of this group will be in Chapel Hill [UNC] this Fall" (Cox to C. and E. Cox, 2 July 1965 in [10]).

Cox was particularly concerned that the education of Egyptian students in statistics, whether at home or abroad, prepare them to assist scientists and researchers in other fields by including "more instruction and experience in the use of statistical techniques." Statisticians teaching graduate students at the ISSR must, she insisted, "be research oriented and preferably should be actively engaged in research" [4]. Research, as Cox used the term here, meant the use of statistical methods to investigate agricultural, social, or economic problems, rather than the creation of new methods or the advancement of knowledge in statistical theory.

Cox had in mind the sort of research she had done in her consulting work at the ISSR. The importance of consulting, she observed, had not received enough recognition from Egyptian statisticians. In a memorandum to the Ford Foundation accompanying her report on the Institute, she noted that "the need for consultant help in statistics by research workers is much greater and more urgent than is realized by the present staff of the Institute" (Cox to Ford Foundation Staff, 11 August 1965, in [8]). She pointed out that many of these research workers (scientists in other fields) had studied abroad "at universities where statistical courses were required and where consulting statisticians were available ... to assist them with their research" [4]. Thus these scientists were prepared to make use of consulting services if the ISSR could provide them.

Statisticians at the ISSR had emphasized research in theoretical statistics, a phenomenon that perhaps had roots in the early history of university statistics training in Cairo. In her first discussions with the Ford Foundation about funding the ISSR, Cox told of an effort in the 1950s to coordinate statistics teaching between Cairo University's Faculty of Commerce and its Mathematics Department. The attempt was unsuccessful, as "all the official and applied aspects were lost to pure mathematical statistics" (Cox to MacEachron, 2 April 1962, in [8]).[23] Cox also attributed some of the current neglect of consulting to its lack of prestige in Egypt. In her letter to Lunenberg, Cox explained that consulting at the ISSR did not "hold the same level of stature as does Math[ematical] Stat[istics]" (Cox to Lunenberg, 19 April 1965, in [8]). Moreover, as she told the Ford Foundation, university administrators in Cairo did not tend to recognize consulting "as part of a University job," so professors at the ISSR had little incentive to take on such work (Cox to Ford Foundation Staff, 11 August 1965, in [8]).[24]

[23] For an account of these efforts from a participant, see [42].

[24] This neglect occurred in other university programs in developing countries. Writing about university courses in Iran, a government official there told Cox that "the emphasis is on theoretical

Cox's reports and letters make clear that she perceived a conflict between the ideas of the ISSR staff and her own sense of what the program there should emphasize. In fact, she continued to sound the call for statistics programs that emphasized practical experience for students long after she left Egypt, so this advice was not confined to the ISSR. Not enough evidence has come to light to confirm that the Egyptian statisticians themselves were aware of the conflict, or even that they consciously preferred to create a more mathematical program than Cox was recommending. Nevertheless, as the next section will show, the establishment of consulting services at the ISSR continued to make only slow progress in the years after Cox's visit.

15.6 Subsequent Developments in Cairo

Following Cox's year at the ISSR, the Ford Foundation sent twelve more program specialists to Cairo. Cox herself recruited the first two, Carl Marshall of Oklahoma State University, and Ralph Bradley, then at Florida State University. As late as May, 1967, while Bradley was in Cairo, the Ford program officer for overseas development, Thomas Scott, was asking Cox for more names of statisticians to go to Cairo in the coming year (Scott to Cox, 23 May 1967, in [8]). The Six-Day War began some two weeks later, as Bradley was returning to the US through Europe. The Ford office in Cairo closed as Americans evacuated the city, but when James Lipscomb returned in January, 1968, the search for a new program specialist continued, now with Bradley's help (Ahmed Sarhan to James Lipscomb, 13 March 1968, Lipscomb to Kingsley, 4 April 1968 in [17]).

Bradley continued to serve the ISSR and the Ford Foundation as a consultant to the Institute, visiting Cairo several times over the next decade, recruiting all but two of the remaining consultants, and writing the Foundation's final report when it closed out its grant to the ISSR in 1978. By then, the Institute had 16 full time faculty, compared with just a single faculty member when it began in 1963. These faculty made up four departments: applied statistics and economics, biostatistics and demography, computer science and operations research, and mathematical statistics. Over 300 students were enrolled in the two-year diploma programs in statistics, computing science, demography, and operations research. The masters of science programs had 40 students, and ten students were progressing through the Ph.D. programs [15].

The Ford Foundation had increased its original 1963 grant to the ISSR with two supplements, a second grant to establish a computing center affiliated with the Institute, and several smaller grants to subsidize conferences held at the ISSR.

aspects of statistical methods rather than on practical and operational aspects" (A. S. Shaheen to Cox, 19 December 1964, in [8]).

When John Hilliard proposed in 1963 that the Ford Foundation assist the ISSR, he speculated that Ford's support would total about $400,000 over five years. In its fifteen years of funding, Ford ultimately provided $1.3 million.[25]

In addition to supporting visiting statisticians, the original grant and its supplements purchased books and journals for the Institute's library and sent 24 Egyptian students abroad for graduate study, with the goal of increasing the Institute's faculty. By the time Bradley wrote his final report, 18 fellowship recipients had completed Ph.D.s, and eight of these were serving as faculty members at the ISSR.[26] As Bradley described it, "the training record of ISSR students at doctoral programs abroad is remarkable." He felt that this aspect of the Ford program "must be judged successful," and that while more than half of Ford fellows were no longer at the Institute, "a contribution ha[d] been made" since most were serving elsewhere in the region [15, p. 25]. The library, for which Foundation support had been essential, had become "the leading library in Egypt in its areas of specialization" [15, p. 33].

Ford officials concurred with Bradley's assessment. When the final supplement to the grant had been made in 1973, the Cairo representative called the ISSR "the most important resource base in statistical training and research in the Middle East," and judged it to be "the most successful Foundation-sponsored activity in Egypt that ha[d] a truly regional impact" (James Ivy to Wayne Fredericks, 15 May 1973 in [16]). In his memorandum filed with Bradley's report, William D. Carmichael, head of the Middle East and Africa department of Ford's International Division, declared the grant a success, writing, "The Foundation's assistance responded to an important need ..., provided a well conceived mix of inputs ..., and was clearly essential ...for the survival and development of the Institute" (William D. Carmichael to Files, 9 June 1979 in [16]).[27]

What had Gertrude Cox contributed to the success of this project? How did her work, her skills, and her passion for promoting statistics training shape the final outcome? Bradley's report, focusing primarily on the impact of the Ford Foundation more generally, does not assess the significance of individual program specialists. Cox's name appears on the list of consultants; Bradley notes her correspondence with Husein when the grant began and her recruitment of Marshall and Bradley; he briefly describes her activities while in Cairo and mentions that she discussed the needs of a computing facility while in Egypt. Otherwise, neither the report nor the comments on it by Foundation officials reveals the extent of her influence.

The fifteen years separating Cox's involvement and the end of the grant explain this omission, in part. By then, Ford had different staff both in the Cairo office and in the overseas office at its headquarters in New York. Back when she finished

[25]This final number comes from (Richard C. Robarts to William D. Carmichael, 21 December 1978, Ford Archives, Grant #63–501). For the original estimate, see (Hilliard to Ward, 6 February 1963 in [16]).

[26]Since completing Ph.Ds, 11 of the 18 had returned to the ISSR, but 3 of these had left by 1978 [15, p. 19].

[27]The ISSR exists today as a division of Cairo University, organized much as it was when Bradley wrote his report.

her time in Cairo, the verdict on her impact had been clear. "She has done an extraordinary job here in getting ISSR off to the best possible start," Lipscomb wrote to the New York office (Lipscomb to Scott, 18 May 1965 in [17]). Echoing this praise in another memorandum, Lipscomb asserted, "Her professional reputation here is so high that I suspect she might be able to get some things done that most other program specialists or consultants we might provide could not" (Lipscomb to Kingsley, 15 September 1965 in [17]). Carl Marshall remarked to Cox on the favorable impression she had made at the Institute. The Egyptians "love you and respect you in both the personal and professional sense," he reported. "I am sure they will not put all your recommendations . . . into operation overnight, but you can rest assured that most of the improvements will be traceable to your efforts while you were here" (Marshall to Cox, 20 October 1965, in [8]).[28]

At the most foundational level, Cox's efforts on behalf of the ISSR began with her creation of the Institute of Statistics in North Carolina. As Cox had described in her earliest conversations with Ford officials, some of the first statisticians in Egypt received their training at the Institute. Four of the 24 Foundation-sponsored fellows studied at UNC, and four of the twelve program specialists who followed Cox had received their Ph.D.s there, including Bradley and the two who followed him, Milton Terry and Lyle Calvin. Bradley and Calvin both helped create university statistics programs of their own—Bradley at Florida State University and Calvin at Oregon State University. Like Cox's North Carolina program, those at Florida State and Oregon State combined graduate training with consultation services to other university departments.

Cox's emphasis on the value of service to research workers in other departments (i.e., consulting) played an important role in the development of the ISSR. Initially, ISSR staff had little success in making consulting a central part of their work. Neither Marshall nor Bradley after him found many opportunities to use their abilities in this area. However, describing a recent conversation about consulting with an Institute faculty member, Marshall assured Cox, "I can see your handiwork in all these things and those seeds of ideas that you so masterfully planted are beginning to show signs of life" (Marshall to Cox, 7 October 1965, in [8]).

While Bradley's verdict in his final report on the success of developing a statistical consulting service at the ISSR was negative, his report makes it clear that at least some interest in statistical consulting had continued from Cox's time to the present. As he put it, "The development of statistical consulting at ISSR has been

[28]That her Egyptian colleagues would hold Cox in high regard, both personally and professionally, is consistent with other anecdotes about her personality and her relationships with colleagues. See, for example, [20]. As with the more general questions about Cox's success as a woman in a male-dominated field, the historical record reveals little about issues of gender and Cox's work in Egypt. The correspondence among ISSR staff, Ford officials, and Cox seem to contain no mention of gender-related tensions or any challenges she faced. The fact that the Egyptian constitution and laws changed under Nasser (president of Egypt from 1954 to 1970), giving women voting rights and increased access to employment and education may have played a role in Cox's experience, but these issues need further exploration.

slow and inadequate. Still an effort has been made and is continuing" [15, p. 44]. In fact, at the time of his report, Bradley was working with Calvin and an ISSR faculty member to get funding from the US Agency for International Development (USAID) for a Statistical Consulting Service within ISSR (*ibid.*).

The slow pace at which consulting developed highlights the significance of Cox's efforts. As she reported while in Cairo, and as Bradley confirmed in his report, Cox had been "actively engaged in consulting within both Cairo University and the University of Alexandria and within government agencies and medical schools" [15, p. 42]. In addition to seeking out consulting opportunities and involving her students in that work, Cox had emphasized the importance of providing such service in her report to the ISSR and Ford when she left. Later consultants, as Bradley puts it, "did do limited consulting on special requests but were less active in seeking opportunities" [15, p. 42]. Though Bradley and his successors promoted statistical consulting less ardently than Cox had, interest at the ISSR persisted, perhaps in part because she had made service to other researchers a priority in her own work and in her advice to the Institute.[29]

Finally, Cox's success in recruiting Carl Marshall and Ralph Bradley must be seen as critical for the success of the Ford Foundation grant. They maintained the momentum that Cox had initiated. Bradley played an important role in the ISSR's efforts to get Ford money for the computing center. Three ISSR fellowship recipients received Ph.D.s from his department at Florida State University. He continued giving advice to the Institute and recruiting visiting statisticians and computer scientists throughout the grant period. As a Ford official wrote in an internal memorandum when the grant ended, "The development of the ISSR owes much to Ralph Bradley" (Richard C. Robarts to William D. Carmichael, 21 December 1978 in [16]). Bradley's connection to the ISSR owed much to Gertrude Cox.

Cox's affiliation with Cairo University, her work there, and her recommendations played an important role in the success of the Ford Foundation's grant. They also provide a glimpse of the passion and talent she had for promoting teaching and research in statistics. When she returned to the United States, Cox continued to exhibit that passion and talent. For the next four years, she taught experimental statistics (part time) at NC State, served as a senior statistical advisor to the Research Triangle Institute, and spent seven months in Thailand, advising universities as they developed their statistics education programs.[30] She continued as the chair of the ISI Education Committee until 1968, and attended every ISI meeting through 1975, three years before her death from leukemia in 1978.

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[29] According to Bradley, the slow pace at which consulting services developed was not unique to the ISSR, or even to programs in developing countries. "The provision of statistical advice and service to research in the various disciplines has been difficult to accomplish everywhere." Researchers outside of statistics had been slow to recognize the role of statistics because of "lack of training and insecurity in the use of statistics." Moreover, as Bradley described, "Many statisticians have been more interested in the development of statistical theory than in the practice of statistics," believing that professional rewards were more likely to come from theoretical research [15, p. 42].

[30] Cox was in Thailand from December 1968 through January 1969 as a consultant with the Ford Foundation, and for six months in 1971 with the Rockefeller Foundation.

In the year following her time in Cairo, Cox gave several talks to students and faculty in university statistics departments. Her remarks suggest that her tenure at the ISSR had influenced her thinking about university statistics programs and had fueled her passion for serving others. Speaking at the North Carolina chapter of the ASA in April, 1966, Cox declared that “since returning from overseas, it almost seems as if I am starting on another campaign.” In this talk and in subsequent addresses given over the next year, Cox called for some changes to university statistics courses. In particular, she advocated combining the teaching of statistical theory with statistical methods and analysis—subjects that usually appeared in separate courses. Echoing some of her advice to the ISSR, she also recommended supplementing the lectures with laboratory work, in which “students would become acquainted with real data and problems” [7].[31]

Along with her opinions about the teaching of statistics, Cox also displayed her passion for using one’s knowledge to help others, and her belief that a good statistician could cooperate with researchers in other fields. “As you must know,” she told her audience at the North Carolina ASA chapter meeting, “to be the kind of statistician I believe is needed so vitally, . . . he must have the ability and willingness to cooperate with other scientists” [5]. In another address, she emphasized that “the effectiveness of consulting statisticians is directly proportional to their ability and willingness to work with the people whom they assist. Statistical scientists have to forget themselves, be completely truthful and willing to share their knowledge” [6].

Back in Cairo, while commenting on the lack of attention given to consulting by ISSR statisticians and the fact that such work did not enhance one’s professional status in Egypt, Cox had told her ISI colleague, Bart Lunenberg, “I’m not seeking local recognition nor advancement so it does not disturb me to serve my fellow men. My main objective is to serve the research workers and they appreciate the help.” (Cox to Lunenberg, 19 April 1965, in [8]). For Cox, this willingness to share knowledge not only benefited the recipients of the assistance, but the statisticians themselves. It not only advanced science, but provided personal satisfaction. She urged the graduate students in her audience to keep these ideas in mind as they began their careers. “Your ambition,” she told them, “should be how much can I give, not how much can I get. Give and your storehouse of memories will overflow” [7]. Cox’s efforts on behalf of Cairo University and her broader work for university statistics education abroad put that advice into action.

15.7 Conclusion

This account of that work uncovers more than the talents, interests, and accomplishments of Gertrude Cox. It also uncovers some unexplored ground in the history of women in American science, prompting the question: “How did Cox achieve such

[31] Cox made a similar recommendation in the April 22 talk. These two talks as well as one given at a conference in August, 1966 (cited below), overlap considerably.

influence, success and recognition, in spite of being a woman?" A more extensive analysis of Cox's career could help answer that question. It might, however, go beyond the obvious need to explain the exceptional, and address an alternative set of questions about women's roles in the promotion of statistics. To what extent did Cox's accomplishments result from her being a woman? Was she socialized and trained in such a way that she took on certain tasks essential to the promotion of the statistics profession more readily and skillfully than her male colleagues? How did the needs of the statistics profession—or of science more generally—in the decades after World War II align with the training and professional opportunities available to women and the expectations they had of themselves?

After becoming chair of the ISI Education Committee, Cox spent months pursuing support for university statistics programs in Africa, work that fell outside her professional responsibilities and for which she received no pay.[32] She met with Ford Foundation officials, recruited established statisticians to serve as consultants, and corresponded with statisticians who wanted help, trying to understand their institutional needs. None of the previous (male) chairs of the Education Committee had been so active. Very few new programs were aided under their leadership. Were they too busy pursuing work that more directly advanced their careers to take on the time-consuming and less rewarding labor of networking and lobbying? While in Cairo, Cox took on a heavy teaching and consulting schedule, aggressively pursuing opportunities to advise and serve—opportunities, again, that brought her no extra rewards. The subsequent (male) program specialists, as Bradley himself admitted, "were less active in seeking" consulting work, responding only to special requests from Egyptian researchers [15, p. 42].[33] Consequently, fifteen years after Cox's visit, statistical consulting at the ISSR was not adequately developed. Why did the men wait to be asked rather than seek opportunities to offer their services?

Cox's commitment to service helped both her own career as an administrator and the statistics community as a whole. This case study, then, provides some new ways to think about the gendered nature of certain scientific activities and roles. It suggests that inverting the cause-and-effect or obstacle-and-accomplishment roles of gender and success can provide a useful tool for analyzing the experiences of women in science. That is, in addition to asking how an exceptionally successful woman overcame the typical obstacles to advancement in the male-dominated world of science, it may sometimes be helpful to consider what qualities she possessed—and her male colleagues lacked—that contributed to her success.

These questions point to somewhat different issues than those surrounding Rossiter's discussion of "women's work" in science [39]. Cox's work was neither invisible nor segregated. She not only worked with male colleagues, but held positions of authority over them. Her contemporaries readily credited her with

[32]Recall her comment to a Research Triangle Institute colleague about the Ford contract "giving status" to her ISI work.

[33]For a clear understanding of this difference between Cox and the subsequent program specialists, it is important to note that they did not seem to have less regard for the importance of consulting. For example, as mentioned above, at the time of his final report to Ford, Bradley was working on a grant proposal to support consulting at the ISSR.

advancing the discipline, though she did not earn her accolades primarily by proving theorems or otherwise directly producing knowledge in the field. She was doing high profile work that everyone acknowledged as important, but not doing it, she claimed, for recognition or advancement. She saw a need for statisticians with ambition to give, not to get; with a willingness to share their knowledge with others, serving their "fellow men." If, as Cox believed, the statistics community needed such people in the 1960s, perhaps women like Cox were even better equipped than their male colleagues to fill the role. Moreover, this component of Cox's success may have implications beyond the issues of gender introduced here. A broader investigation into the work of statisticians who participated in technical assistance to developing countries during this period might find that the most successful had a willingness to set aside the advancement of their own scholarly careers in favor of service to the broader community.

The record of Cox's contributions to the ISSR in Cairo certainly reveals that she had the skills and knowledge to play a crucial role in its development. The analysis of that record indicates that the ISSR, the Ford Foundation, and the statistics community in the United States were part of a much larger web of institutions impacting the international development of the discipline. This case study has uncovered some features of that network and proposed some theses about the institutions involved. It has also raised further questions, suggesting lines of research that, if pursued, would add significantly to our understanding of the history of science after World War II.

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Chapter 16
Norma G. Hernandez: A Pioneer

Luis Ortiz-Franco

Abstract This chapter highlights some of the accomplishments of Norma G. Hernandez. She earned her B.A. in Mathematics in 1954, and received her Ph.D. in Mathematics Education in 1970. She is one of the first U.S.-born Latinas, and possibly the first U.S.-born Latina, to receive a Doctorate in Mathematics Education in the United States. This narrative provides general biographical and academic information about Hernandez in the context of an ethno-history framework. Some observations highlight Hernandez's pioneering contributions to Mathematics Education and Ethnomathematics in the early 1970s. In addition, there is a discussion of familial factors that contributed to fostering her early interest in mathematics. At the conclusion of the chapter, some of Hernandez's academic works beyond Mathematics Education are mentioned.

Keywords Norma Hernandez • Mathematics education • Biography • Ethno-history • Latina

16.1 Introduction

This narrative provides a brief biographical sketch of Norma G. Hernandez and a general outline of some of her pioneering academic accomplishments. Hernandez is a pioneer in Mathematics Education in two aspects. One aspect is in educational attainment. She is one of the first U.S.-born Latinas, and possibly the first, to receive a Ph.D. in Mathematics Education in the United States.[1] She earned her doctorate

[1]Initially, Hernandez was uncomfortable with this assertion because she vaguely remembered collaborating with another Latina graduate student but did not precisely recall her name or her field of study. Bertha Alicia Gamez Trevino was born in the U.S. and received her doctorate from UT Austin in 1968, two years before Hernandez. I mentioned this fact to Hernandez in Spring 2017 and Hernandez said: "Yes, Bertha is what I partially recall. That's the name of the person I mentioned. I only vaguely remember her name, but she did work with Glenadine Gibb. I worked with Trevino

L. Ortiz-Franco (✉)
Chapman University, Orange, CA, USA
e-mail: ortizfranco@gmail.com

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from the University of Texas at Austin (UT Austin) in 1970. The other aspect in which Hernandez is a pioneer is in her contributions to research in the teaching and learning of Mathematics for Latino students in grades K–12. Those contributions are mentioned later in the chapter.

Hernandez's life and academic work took place in a multi-cultural context. This chapter begins with a description of the multi-cultural context of Hernandez's early life environment followed by a discussion about her personal experiences in academic life.[2] The chapter concludes with comments about her scholarly work. Hernandez variously identifies herself as Mexican, Chicana, Hispanic, and/or Latina. This nomenclature is used when referring to the Mexican descent population in the U.S. (Figure 16.1).

16.2 El Paso: Hernandez's Birthplace

Hernandez was born in El Paso, Texas on May 19, 1934. El Paso is located in the southwest corner of Texas; the city borders southern New Mexico on the North, and Ciudad Juarez, Mexico, across the Rio Grande, on the South. El Paso and Ciudad Juarez are sister cities; they are connected by several international bridges. The two cities were one city before 1848 when the United States created the international border at the conclusion of the U.S.-Mexico War in 1848.

to help her interpret some of her data as it related to Mexican American students. If I remember correctly, she was not so much into mathematics as she was into early elementary teaching that involved arithmetic" [11]. Trevino's dissertation was titled, "An analysis of the effectiveness of a bilingual program in the teaching of mathematics in the primary grades." From this I determined that the earlier degree was not quite in Mathematics Education but some people may consider it as so. There may also be other earlier PhDs that could be discovered in future archival research, but if so, I did not find them through my interviews. Regardless, Hernandez is certainly one of the early U.S.-born Latina PhDs in this area, if not the first.

[2]Data for this chapter was collected from Hernandez's written responses to a questionnaire designed by myself and administered to her and twenty other Latinos in Mathematics or Mathematics Education in the mid-1990s. Through that medium, I collected basal biographical information from over twenty Latinos in Mathematics or Mathematics Education with the purpose of producing published materials to motivate Latino youth to consider pursuing mathematics-based professions. In addition, in preparing this chapter, I contacted Hernandez by internet to inform her about this project and solicit her collaboration, and to request additional information. She agreed to participate, and I collected information from her in Summer 2016 and Spring 2017. In addition, Hernandez and I participated in panel discussions during an international Mathematics Education conference while collaborating on a book project for the National Council of Teachers of Mathematics (NCTM). The international conference took place in Morelia, Michoacan, Mexico in 1998. The book, *Changing the Faces of Mathematics: Perspectives on Latinos*, was published by NCTM in 1999.

Fig. 16.1 Norma G. Hernandez, 1980

In 1848, English-speaking white people migrated to the area after the conclusion of the U.S.-Mexico War (1846–48). The new colonizers referred to themselves as Americans and imposed a new social order in which they had the highest social status, followed by the social structure previously established by the Spanish when they were the colonial rulers. Moreover, to the new colonizers, all of the people living in El Paso at the time of their arrival were Mexican. As noted above, a border was created between the U.S. and Mexico where none existed before. According to scholar Mario T. García:

> Those Mexicans who remained north of the new border following the conflict not only lost their family and communal lands but became subject to racial and political discrimination as well as cultural erosion. Their eventual second-class status set the pattern for the later treatment of Mexican immigrants [5, p. 1].

Furthermore, García attributes a prominent role to El Paso in Mexican immigration to the United States with the observation that El Paso was the largest port of entry between 1880 and 1920. He goes on to say:

> El Paso is the most important American city along the United States-Mexican border. El Paso symbolized to Mexicans what New York represented to European immigrants: the opening of what they believed could be a better life [5, p. 2].

In discussing U.S. immigration from 1820 onward, Louis DeSipio and Rodolpho O. de la Garza include data showing that Mexico has been among the four countries contributing the largest number of lawful immigrants since the 1940s. In fact, according to their data, Mexico has contributed the largest number of lawful immigrants to the United States from the 1960s to the 2000s [4, Table 2.3, pp. 54–57]. In addressing immigration from around the world to the United States, the authors go on to say that

> By the 1990s and the first decade of the twenty-first century immigration to permanent residence grew to approximately 1.1 million annually. These legal immigrants were supplemented by a 300,000–500,000 new unauthorized immigrants who took up residence in the United States each year, at least until 2008, when their numbers began to decline in response to a slowed U.S. economy and stricter enforcement against unauthorized immigration [4, p. 77].

A significant portion of this flow of people passed through El Paso.

In modern times, the El Paso area is a vibrant, multi-cultural, bilingual Spanish-English environment. The residents of the city consist of descendants of the native peoples, the Spanish, American, and Mexican colonizers, and lawful and unlawful immigrants. Hernandez was born, raised, and educated in that social world.

16.3 The Early Years

Hernandez's parents were Manuel Gonzalez, Sr. and Ramona Rodriguez. Hernandez is second generation American on her mother's side and first generation on her father's side. Her mother was born in El Paso in 1906 and graduated from El Paso High School in 1925. In those days, that was considered to be a relatively high level of educational attainment in American culture and more so in the Latino community in El Paso. Ramona's educational accomplishments are all the more remarkable when we consider the following comments by García. He says that the education that Mexican-descent children received was very inferior compared to the education white American children received. "From their inception [in 1883] El Paso public schools segregated most Mexican children" [5, pp. 110–111], and school officials believed that the "…Mexican schools should direct their attention to manual and domestic education that would help students find jobs …. What little schooling the Mexicans did acquire, moreover, took place in highly congested buildings …" [5, pp. 5–6].

Hernandez's father, Manuel, was born in Zacatecas, Mexico in 1903. He immigrated to El Paso in 1917, during the last part of the Mexican Revolution that began in 1910. He finished the equivalent of the freshman year in high school in Mexico; he was considered well-educated by Mexican society standards at the time. Manuel's family owned a small hardware store in Mexico and, thus, was considered to be middle-class.

Hernandez is the oldest of four surviving children in her family; she has twin brothers and a sister. All four siblings became college-educated professionals. One brother, Manuel, is an electrical engineer; the other, Ismael, is a pharmacist. The youngest, Sandra, is a high school teacher of History and Spanish.

In Hernandez's family, Spanish was the dominant language, and English was the second language. She grew up in an extended family that included two aunts and a cousin. They all lived in a three-bedroom apartment, with a living room-dining room, a kitchen, and a bathroom. One of her aunts, Josefa, earned a teaching certificate in Mexico before coming to the United States and Josefa taught school in Ciudad Juarez, commuting daily across an international bridge. She eventually became a school principal in Mexico and later became the equivalent of a public school superintendent.

Aunt Josefa was a major influence on Hernandez and her siblings. She taught them how to write in Spanish, and, subsequently, Hernandez used her familiarity with phonetics to learn how to read and write English. Josefa also taught Norma and Sandra about Mexican history and their family's struggle during the 1910–1920 Mexican Revolution. Education was highly valued in the family due to the relatively high educational levels of the parents and Aunt Josefa. The family expected Norma and her siblings to become college-educated professionals.

Later, Norma's family owned a home and a medium-sized corner grocery store run by Norma's mother. Her father worked as a sales clerk in a shoe store during the week and in the family store on Sundays. When Norma was old enough, she managed the store after school.

Norma showed an interest in mathematics at an early age, and the store provided her the opportunity to both do her homework and polish her math skills. While tending the store, she would practice mental arithmetic skills when adding the bills, giving change and computing percentages. She also practiced problem-solving in the context of consumer mathematics. Hernandez says "that those experiences contributed to making me feel comfortable in mathematical problem-solving tasks by my early teens" [9].

The multi-cultural community in El Paso impacted Hernandez's academic life in a number of ways. As stated before, El Paso has a history of segregated schools, reflecting residential areas segregated along socio-economic and ethnic lines. People living on the south side of the railroad tracks, then and now, are mostly non-white and living at a lower-socioeconomic level. The children in those families attend ethnically segregated schools which tend to be poorly funded. Fortunately for Hernandez, her family lived on the north side of the tracks which enabled her to attend integrated schools that were about 50% white and 50% non-white. Hernandez remembers that the white students, and especially the white girls, in her elementary and secondary schools were very discriminatory toward students of Mexican descent. The sting of gender discrimination was layered on top of ethnic discrimination in mathematics classes in high school and, later, college.

Hernandez believes that despite earning many academic honors throughout high school, such as honor roll, honor society, and outstanding student of the month in STEM subjects, she was not chosen to be class valedictorian because she was both of Mexican descent and a female. She remembers that "a white male student with equal academic accomplishments in some subjects, but lesser academic accomplishments in others, was selected valedictorian" [9].

Gender and ethnic discrimination against Hernandez continued in her university and her professional life. This occurred when she interacted with highly educated colleagues. Hernandez noticed that the higher she progressed on the educational and career ladder, the more subtle racism and sexism against her became. When I asked Hernandez what social or psychological strategies she used to overcome the impact of those experiences, she responded: "…It's ironic I used the fact that

I was a very capable female instructor in mathematics who had published in a number of recognized mathematical education journals as a shield against visible and implied discriminatory action used against me" [10]. Furthermore, Hernandez believes that her professional colleagues quite frequently did not acknowledge her accomplishments because of their racist and sexist discriminatory tendencies. She handled those attitudes, as many other women and ethnic minorities do, by becoming stronger and more productive. She said: "…Many females, myself included, in executive positions have to be more effective, productive and hardy than their male colleagues. Unfortunately, many in academia see a sensitive, caring administrator as a weak and less than 'intelligent' associate" [10]. Moreover, Hernandez believes that her "greatest challenge was how to be a good mother and an accomplished professor at the same time" [9].

16.4 Marriage and Family

Hernandez met her husband, Rodolfo Hernandez, in church in El Paso in 1952. Two years later they were married. Rodolfo became the director of the laboratory of the El Paso Health Department. He and Norma had four children, all girls: Raquel, Rebecca, Ruth, and Miriam Xochitl. All four are university-educated. Raquel has a Ph.D. in Microbiology/Virology from UT Austin; Rebecca, an M.S. in Microbiology from UT Austin; Ruth, an RN from the University of Texas at El Paso (UTEP); and, Miriam Xochitl, a BA from UTEP. These four daughters gave their parents six accomplished grandchildren, all of whom completed, or plan to complete, university degrees.

16.5 Professional Career

Hernandez matriculated at Texas Western College (TWC) immediately after graduating from high school. She majored in mathematics and remembers being the only female student in all of her advanced mathematics courses. In 1954, she received her Bachelor of Arts degree in Mathematics from TWC. This academic accomplishment possibly makes her one of the first American-born Latinas to receive a degree in Mathematics from an accredited college in the United States. Concerning the major influence that led her to study mathematics, she says: "…I believe that the major factor in my life that influenced me to become a mathematician was the opportunity to learn mathematics in the supportive atmosphere that my parents provided me" [9].

In 1955, upon graduating from TWC, Hernandez started working as an elementary school teacher at the El Paso Independent School District. Two years later, she transferred to the Austin School District and remained in Austin for three years. In 1960, she earned her MA in Mathematics from UT Austin. Hernandez says that she chose teaching as a profession because she enjoyed the intellectual interaction with other people. By her own admission, she was more successful in influencing Latino boys, compared to girls, to pursue math-based careers when she taught in grades K–12. At least seven of her former students became engineers at NASA or White Sands, New Mexico, or completed advanced degrees in mathematics-related fields [9].

Concerning the difference in her success with boys, as compared to girls, Hernandez says, "…It wasn't so much that I was more successful teaching boys; it was that I worked MORE with boys than with the girls. As per the blindness of the time, it was more important that the boys work in mathematics related areas than girls. I have certainly changed my attitude since those days" [11]. She remembers that she "visited their [the boys'] homes to talk with parents regarding future educational opportunities in mathematics.… I also talked to all my classes about the reason I had chosen the SMSG [School Mathematics Study Group] mathematics program for them—it would help them learn mathematics and help them in learning thinking skills" [11].

Hernandez returned to the El Paso School District to resume her teaching career after finishing her MA degree in Austin, but she soon became interested in educational curriculum issues. She became Supervisor of Secondary Mathematics and continued in that position until 1967, when she commenced her doctoral studies in Mathematics Education at UT Austin. In 1970, Hernandez completed her Ph.D., becoming perhaps the first U.S.-born Latina to receive a Doctorate in that discipline. Her dissertation was titled, "An observation system to analyze cognitive content of teacher discourse in a mathematics lesson."

Upon receiving her Ph.D., Dr. Hernandez began her university academic career as Assistant Professor in the College of Education at UTEP. She remained at UTEP until she retired in 2000. Throughout her career at UTEP, Hernandez taught, performed administrative duties, and authored many articles in professional journals. She also authored, individually and as a co-author, several books on socio-political topics affecting Latinos in the U.S., and she wrote monographs on various educational topics. She also participated in many national and international professional conferences on Mathematics Education.

The multicultural environment in which Hernandez grew up influenced her pioneering activities in Mathematics Education. In one of her early publications, the article "Mathematics for the Bicultural Student" [6], she examined the relationship between culture and mathematics and used her findings to advance ideas about mathematics instruction for bicultural students. In that article, she reviewed the literature on teaching strategies in mathematics for field-dependent and field-independent students and recommended that time and effort be spent in the reorganization of content in order to provide a variety of curricular experiences for all students. She also alluded to the nature of culture and made the observation that "…mathematics is but another example of man's capacity to humanize reality by counting, measuring, expressing relationships" [6]. Those seminal thoughts presaged the fundamental concepts of Ethnomathematics as postulated by Ubiratan

D'Ambrosio at the 5th International Congress on Mathematics Education (ICME 5) in Adelaide, Australia in 1984 (see [3]), and by Alan Bishop in his 1991 book, *Mathematical Enculturation* [2].

Hernandez again advanced new ideas in her article "Variables Affecting Achievement of Middle School Mexican-American Students," published by the American Education Research Association (AERA) in 1973. In that article, she advocated the integration of language, culture, and parental suggestions in the development of mathematical curriculum and the teaching of Chicano students. She observed that "... Community participation in curriculum development must be of a deep and concentrated nature ... It is through the efforts of such community representation that relevance can be brought into the education scene" [7, p. 24]. Hernandez also addressed the topic of culture in education when she wrote that culturally different children need "a different kind of attention" and that "... teachers can be prepared through pre-service and in-service activities to develop these knowledge, understandings, skills, and attitudes needed to teach culturally different children" [7, p. 27]. In the same year, Edward Begle of Stanford University, based on his research findings in the School Mathematics Study Group (SMSG), urged us not to ignore culture in mathematics education [1].

Hernandez learned from her life experiences in El Paso that immigration from Mexico to the United States is ever-flowing, albeit at variable rates depending on the prevailing socio-economic circumstances in both countries. Based on that knowledge, she and Jorge Descamps observed, "... Since the flow of Mexican immigration is continuous, the Mexican-American community can be viewed not as a homogenous group sharing many similar characteristics but as a series of groups moving across a continuum of acculturation at different speeds and thus creating a very complex profile" [8]. For instance, according to a 2015 Pew Research Foundation analysis, "From 2009–2014, one million Mexicans and their families (including U.S.-born children) left the U.S. for Mexico ... [while] an estimated 870,000 Mexican nationals left Mexico to come to the U.S." [12]. That complex immigration profile must be considered when addressing socio-economic and educational matters pertaining to the Latino population in the U.S. (Figure 16.2).

16.6 Closing Remarks

In addition to the pioneering contributions that Professor Hernandez has made to Mathematics Education, she published chapters in books dealing with social issues and education and wrote monographs recommending exciting areas for research into the education of Mexican-American students. She also co-edited two books with Roberto E. Villarreal, published by Greenwood Publishing Co.: (1) *Latino Empowerment: Progress, Problems, and Prospects*, published in 1988 (also with Howard D. Neighbor), and (2) *Latinos and Political Coalitions: Political Empowerment for the 1990s*, published in 1991. As the titles indicate, the volumes deal with various issues pertaining to political issues affecting Latinos.

Fig. 16.2 Professor Emerita Norma G. Hernandez, 2016

Professor Hernandez has served her local El Paso community as well as the academic community. In one of her many local activities, she chaired the El Paso Committee of the Texas State Sesquicentennial Celebration. At UTEP, in addition to serving on many faculty committees, she was the Dean of the College of Education for six years. When she retired, she was the Chairperson of the Department of Educational Psychology and Special Services.

Professor Hernandez is now retired and living in Austin, far from her native El Paso, but always attentive to issues related to the mathematics education of children and their teachers, and especially that of children of Mexican descent.

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Part III
Education and Outreach

Chapter 17
Modern and Pure: Teaching Geometry in Early Twentieth-Century Women's Colleges

Jemma Lorenat

Abstract In 1913 *The American Mathematical Monthly* published an article encouraging the inclusion of synthetic projective geometry in the undergraduate curriculum. The author, William Henry Bussey, lamented that American colleges and universities rarely taught the subject despite its potential for industry, teachers, and the liberal arts curriculum. The following year Lao G. Simons responded in "hearty sympathy" describing the potential of synthetic geometry in broadening "the minds of prospective high school teachers." Both Simons and Bussey particularly remarked on the success of the course at women's colleges. Simons herself taught at the Normal College of the City of New York and referred to the appreciation "the girls" had of the subject. Bussey observed that "Bryn Mawr, Mount Holyoke, Smith, Vassar, Wellesley, Wells, and Goucher College of Baltimore" regularly featured the course. Drawing on college catalogs, faculty publications, department histories, course notes, and textbooks, this paper will examine the diverse reasons for teaching this modern pure geometry at women's colleges in the decade following 1913.

Keywords Projective geometry • Women's colleges • Mathematics education

17.1 Introduction

William Henry Bussey, a professor at the University of Minnesota, was upset about the status of synthetic projective geometry in American college education. In his article, "Synthetic Projective Geometry as an Undergraduate Study," published in the *The American Mathematical Monthly* in 1913, he lamented that

> Synthetic projective geometry is still overshadowed by analytic geometry and the calculus and it does not have the place in the undergraduate curriculum that it ought to have. Indeed it may be said that it has no recognized place, for in most American colleges and universities it is not offered at all, and there is nothing like uniformity in the conditions under which it is offered in those that do give a course in the subject [4, p. 273].

J. Lorenat (✉)
Pitzer College, 1050 North Mills, Claremont, CA, USA
e-mail: jlorenat@pitzer.edu

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By "projective geometry" Bussey meant the geometry that encompassed such concepts as points at infinity, the principle of duality and anharmonic (or cross) ratios. Synthetic, as opposed to analytic, geometry did not employ coordinate equations and so was also known as "pure" geometry. He emphasized that the subject had emerged in France and Germany during the early nineteenth century, and remained an area of active research. However, Bussey did not advocate projective geometry for undergraduates interested in mathematical research, suggesting that such students would be better suited to take the course in graduate school. Instead, he pointed to the potential benefits for "those who are going to college for a liberal education and who are taking mathematics because they like it and not because they expect to use it; and those who are taking mathematics in college as a preparation for teaching mathematics in the high school" [4, p. 274]. For the former group, he noted that many students preferred geometry to algebra, and synthetic projective geometry offered a "more interesting" opportunity to expand upon these preferences. Moreover, he observed that while most colleges prepared future teachers of algebra with courses in analytic geometry, calculus, determinants and the theory of equations, there was no equivalent line of study for future teachers of geometry. Nevertheless, geometry remained a cornerstone of the high school curriculum and a necessary prerequisite for college admission. Bussey pointed out how synthetic projective geometry mirrored and extended high school geometry with ruler constructions, logical reasoning, and general principles beyond the "synthetic geometry of the Greeks."

Despite the lack of a suitable textbook and a uniform curriculum, Bussey observed that projective geometry was not wholly absent from the college landscape. In particular he drew attention to "a significant fact that most of the prominent colleges for women offer courses in synthetic projective geometry to junior and senior undergraduates. Bryn Mawr, Mount Holyoke, Smith, Vassar, Wellesley, Wells, and Goucher College of Baltimore do so" [4, p. 273]. Bussey added that those at coeducational colleges taking mathematics in preparation for teaching were mostly "young women." Thus he suggested that projective geometry was especially useful in addressing the pedagogical aspirations of female students.

The correlation between women and synthetic projective geometry reappeared in *The American Mathematical Monthly* with Lao G. Simons' article "A Note on Synthetic Projective Geometry" in 1914 [36]. Simons had been teaching projective geometry at the Normal College of the City of New York (at the time an all women's college and which would be renamed Hunter College in 1914) for the past five years. She detailed the course topics in her one-semester upper-level course, explaining that "only pupils who are really interested in mathematics are advised to take this course." As a result "the girls enjoyed the work" and found in it "the great enjoyment that a mathematics student experiences when he [sic] has arrived at a definite conclusion through steps of pure reasoning, when he has proved a fact true that was not at first apparent" [36, p. 101]. Like Bussey, Simons noted the particular connection between learning projective geometry in college and teaching elementary geometry in high school. Moreover, she drew attention to the report of the Committee of Ten on secondary school studies from 1894. The section on mathematics had been written by a distinguished group of American mathematicians and concluded with a call for modern geometry, which Simons quoted in full.[1]

> A place should also be found either in the school or college course for at least the elements of the modern synthetic or projective geometry. It is astonishing that this subject should be so generally ignored, for mathematics offers nothing more attractive. It possesses the concreteness of the ancient geometry without the tedious particularity, and the power of analytical geometry without the reckoning, and by the beauty of its ideas and methods illustrates the esthetic quality which is the charm of the higher mathematics, but which the elementary mathematics in general lacks [23, p. 116].

A note on language is necessary before proceeding further. Bussey and Simons wrote about Synthetic Projective Geometry and we will see that this area of study might also be referred to as pure geometry, modern geometry, or the geometry of position. Though modern pure geometry was not always an identical subject to synthetic projective geometry or geometry of position, the variation between names seems based more on personal choice than systematic or predictable differences. Thus, unless employing a direct citation, in the following we will use "modern pure geometry" to refer to the general area of non-coordinate projective geometry that includes the principles, methods, and elements introduced during the early nineteenth century. This designation has the advantage of dating back to Poncelet's introduction of the subject in 1817 [24].[2]

Our study will test the extent to which teaching high school geometry motivated the teaching of modern pure geometry at undergraduate women's colleges. Drawing from the viewpoints suggested by Bussey and Simons, this chapter focuses on the curriculum at Bryn Mawr, Mount Holyoke, Smith, Vassar, Wellesley, Goucher,

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[1]The Conference in Mathematics met in December of 1892 and consisted of Simon Newcomb, William E. Byerly, Arthur H. Cutler, Florian Cajori, Henry B. Fine, W. A. Greeson, Andrew Ingraham, George G. Olds, James L. Patterson, and T. H. Safford.

[2]In 1872 Luigi Cremona debated the alternate names of this new form of geometry and came to a different conclusion.

> Various names have been given to this subject of which we are about to develop the fundamental principles. I prefer not to adopt that of *Higher Geometry (Géométrie supérieure, höhere Geometrie)*, because that to which the title 'higher' at one time seemed appropriate, may to-day have become very elementary; nor that of *Modern Geometry (neuere Geometrie)*, which in like manner expresses a merely relative idea; and is moreover open to the objection that although the methods may be regarded as modern, yet the matter is to a great extent old. Nor does the title *Geometry of position* (*Geometrie der Lage*) as used by STAUDT seem to me a suitable one, since it excludes the consideration of the metrical properties of figures. I have chosen the name of *Projective Geometry*, as expressing the true nature of the methods, which are based essentially on central projection or perspective. And one reason which has determined this choice is that the great PONCELET, the chief creator of the modern methods, gave to his immortal book the title of *Traité des propriétés projectives des figures* (1822) [14].

Nevertheless, even fifty-years after Cremona, the designation among geometries was far from uniform, and most authors seemed to understand any of the above terms as roughly equivalent.

and Hunter College, in the decade following 1913.[3] As such, this study is not exhaustive with respect to women's colleges (of which there were dozens in the early twentieth century) nor the teaching of modern pure geometry.[4] However, Judy Green and Jeanne LaDuke have shown in their book that among women who earned their PhDs in America before 1940, these seven women's colleges educated and employed a substantial proportion of women mathematicians [17]. Thus, if not wholly representative of the entire population, the courses at the above-mentioned institutions still reveal a range of motivations and approaches.

The following exploration will show that though the teaching of modern pure geometry often served anticipated pedagogical goals, this was not its only possible role at women's colleges. Instead, we will show a lack of consensus even among this small group of women's colleges, which reflects the varied motivations for women's mathematics education in this time period. Modern pure geometry could not only educate future teachers, but also inspire future researchers and inculcate mathematical thinking in the curious liberal arts student.

The first section of this chapter examines course catalogs from 1913 to 1923. These brief summaries included course titles, occasional descriptions, teaching faculty, preparatory and supplementary courses, dates and times, as summarized in the accompanying table. Analyzing the catalog contents provides an overview of how geometry functioned in the mathematics curriculum for undergraduate majors and minors, for graduate studies, and for the general liberal arts student. The span of a decade reveals the diversity of geometry courses across the colleges as well as the consistency of offerings and instructors at each institution.

To delve deeper into the culture of geometry on these campuses, the second section focuses on the individuals who taught these geometry courses. Alongside teaching geometry, faculty also engaged with geometry by conducting original research, debating pedagogical issues, composing textbooks, and reviewing international publications. A survey of these writings as they relate to modern pure geometry will further illuminate the motivations behind course offerings.

In the third section, the content of geometry courses will be explored through lecture notes, textbooks, and department histories. Here we will examine how the specific methods and elements of modern geometry might simultaneously serve diverse departmental goals in training students of mathematics.

Progressing from course titles, to faculty activities, to course contents will reveal how women's colleges taught modern pure geometry. As we will see, different facets of the subject could be emphasized to serve individual institutional or faculty aims. These differences could even seem contradictory. Modern geometry was celebrated as at once requiring concrete constructions and demanding purely mental

[3]We exclude Wells College as we have been unable so far to obtain any course materials from this institution.

[4]The recent Cajori Two Project shows that, in contrast to Bussey's observations, courses classified as projective geometry were taught at diverse institutions including Colorado College, Johns Hopkins, Stanford, Berkeley, and University of Wisconsin at Madison in the year 1915.

imagination. The courses often required very few prerequisites, but some allowed students the rare opportunity to engage with contemporary research. Rather than a deterrent, the multiple possibilities of modern pure geometry demonstrate why the subject formed a core component of the mathematics curriculum at women's colleges.

17.2 College Catalogs

With the exception of Bryn Mawr, all seven colleges surveyed usually offered an undergraduate course on some version of modern pure geometry. As the tables in our accompanying appendix indicate, the course titles included some combination of modern, synthetic, projective, or pure geometry.

Descriptive geometry, whose origin is attributed to Gaspard Monge in the late eighteenth century, was usually limited to orthogonal projection, and thus constituted a different but related subject. However, this was not always the case. At Smith College the course entitled Descriptive Geometry was described as "Geometry of Position using the Holgate translation of Reye" [70]. Theodor Reye's *Geometry of Position* was also the textbook for Projective Geometry at Mount Holyoke [59]. A similar connection between the subjects can be observed at Wellesley after 1918, where Descriptive Geometry and Modern Synthetic Geometry could not both be counted toward the B.A. degree [85]. Thus, there appears to have been overlap between course content and accordingly we included all Descriptive Geometry courses in our table.

While some form of modern pure geometry was never a required course for the major or other subsequent higher level courses, prerequisites varied between institutions. The general expectation seems to have been that these courses were intended for the third and fourth year of study. Vassar and Hunter required analytic geometry as a prerequisite [69, 90]. Wellesley restricted Modern Synthetic Geometry to students who had completed or were currently enrolled in differential and integral calculus. Prior to 1922, students at Goucher could take Pure Projective Geometry following Plane Analytic Geometry, but in the 1922/1923 academic year the course prerequisite changed to include one year of Differential and Integral Calculus [54, 58].

At Bryn Mawr, Charlotte Angas Scott only offered Lectures on Modern Pure Geometry as a post-major course approximately every other year.

> The post-major courses in mathematics are designed to bridge over the interval between the ordinary undergraduate studies and advanced work. They deal, therefore, with the subjects of the major course, carried to higher developments and treated by higher methods. As the order of mathematical studies differs in different colleges, graduate students frequently find it advisable to devote a part of their time to these courses. Regular written work is expected from all mathematical students, and a reading knowledge of French and German is presupposed [44].

Undergraduates were not permitted to enroll before taking the degree. The language requirement, also mentioned for mathematics majors at Smith, allowed students to read a much broader scope of original research.

Only at Smith do we find a progression of courses, from descriptive to projective to "Projective Geometry with Especial Reference to Imaginaries." The description of the final course simply states: "*Beiträge zur Geometrie der Lage* [*Contributions to the Geometry of Position*] by K. von Staudt" [74]. This text, published in three volumes between 1856 and 1860, extensively treats complex projective space and was intended by its author as a continuation of his geometry of position.[5] Thus, we may presume that this course was limited to select students who knew both German and the fundamentals of projective geometry.

Titles, requirements, and durations varied between institutions, but course instructors remained fairly constant at each institution over the ten-year period. Mathematics departments at these institutions ranged in size from two to nine faculty members, who had stated terminal degrees ranging from bachelors to doctorates. Despite this variation, modern pure geometry professors rarely changed. This is particularly apparent at Smith, Goucher, and Bryn Mawr, where Harriet Redfield Cobb, Clara Bacon, and Charlotte Angas Scott respectively taught the only such courses. The commitment to projective geometry among these faculty suggests a genuine interest in and dedication to the subject.

17.3 Faculty

The faculty who taught some version of modern pure geometry ranged from department chairs to visiting instructors. Excerpts from their publications in research and pedagogy shed light on their philosophies and practices of teaching.[6] Modern pure geometry could advance faculty research projects and solve perceived problems in mathematics education.

Scott stands out as one of the most famous women mathematicians of the late nineteenth and early twentieth centuries. Though her research was primarily in analytic geometry, several of her writings treat the foundations and consistency of modern pure geometry, often with respect to teaching [29, 30, 32–35]. Scott clearly stated her concerns in a short article on "The Status of Imaginaries in Pure Geometry"

> In teaching the elements of analytical geometry we are practically forced to allow, even to encourage, a slipshod identification of the field of geometry with the field of algebra. We must all have realized the disadvantages attendant on this course. If ever we have the chance

[5] For the publication and influence of Karl Georg Christian von Staudt's books, *Geometrie der Lage* and *Beiträge zur Geometrie der Lage*, see [25].

[6] Additional biographical information on many of the women mathematicians cited here can be found in [17].

> of repairing the error–if error indeed it be at that stage–it is in teaching synthetic geometry; but we can repair it then only if we can establish the existence of imaginary elements without the slightest dependence on algebra. [...] It is one of the axioms of modern mathematics that von Staudt placed the doctrine of imaginaries on a firm geometrical basis; but logical and convincing as his treatment is, when patiently studied in all its detail, it yet seems to me hardly practicable as a class-room method [31, p. 163].

Scott proceeded to show how von Staudt "extends his domain beyond the visible universe" to include imaginary elements. He then showed that these imaginary elements possess the same properties as "natural" elements and that there are no other imaginary elements beyond the ones he initially defined. Because of the pedagogical difficulty of von Staudt's treatment, Scott suggested an approach combining aspects from von Staudt and Reye's *Geometrie der Lage*. Unlike von Staudt, Reye began with all points, lines, and planes and then classified them, in Scott's words, into "picturable" and "non-picturable." Scott preferred this approach for teaching beginners as it was more direct and justified "the use of diagrams in proving results that depend on so-called imaginaries" [31, p. 168]. She concluded this recommendation modestly.

> This is merely intended as a suggestion to practical teachers; it is not set forth as a fully worked out scheme. A different formulation of the relations and properties may be preferable, but I believe the principle to be sound [31, p. 167].

Scott returned to von Staudt's treatment of imaginaries in a three part series published in *The Mathematical Gazette* in 1900 [32–34].

However, even by 1900, von Staudt's detailed non-metric imaginary elements were not often applied in contemporary research. Rather, as Scott readily admitted, an understanding of von Staudt primarily served to justify the use of imaginaries within the teaching and foundations of modern pure geometry. Scott thus suggested an additional motivation for "teaching synthetic geometry" as a means of independently justifying the use of imaginaries in geometry without reference to algebra [31]. Further, Scott had argued in an earlier review that "all teachers of even the most elementary geometry" should be introduced to concepts from "modern" geometry [28]. Her accessible presentation of imaginaries thus aimed to serve a wide potential audience of high school teachers, even if imaginary elements remained outside the high school curriculum. Appearing around the turn of the century, Scott's interpretation of von Staudt closely aligned with contemporary developments in modern algebra and foundations of mathematics. Her consistent course offerings suggest that she continued to promote the explanatory power of synthetic geometry through the early twentieth century.

Like Scott, Henry Seely White's voluminous research focused on algebraic and analytic geometry. Nevertheless, White regularly taught a course on Synthetic Projective Geometry at Vassar. In an article on "How Should The College Teach Analytic Geometry?" he advocated for the inclusion of projective geometry [40]. This article, originally read before the Association of Teachers of Mathematics of the Middle States and Maryland in 1905, offered a corrective to "recent college text-books" and was aimed at the liberal arts curriculum. White began by celebrating the rich history of projective geometry and particularly the study of conics from ancient times through Jakob Steiner and Otto Hesse. He suggested that students could find a model for future research in this history. As he queried, "How can one learn what kind of questions will prove fruitful, save by examining those which have been asked and answered by geometricians in the past?" [40, p. 494]. White described the theory of conics as a "model both in the large number of its particular propositions and in the possession of general concepts and theorems." From these few general concepts and theorems, students could learn to deduce many of the familiar propositions from elementary geometry alongside more modern results. Although presented in the context of analytic geometry, White's proposal for the study of projective geometry remained equally valid for modern pure geometry. Through its history and generality, pure or analytic projective geometry could show students how to choose fruitful questions and undertake "explorations on their own account" [40, p. 497].

White's colleague at Vassar, Elizabeth Buchanan Cowley, taught Descriptive Geometry and Mechanical Drawing. Her own research in modern analytic geometry resulted in a dissertation on *Plane Curves of the Eighth Order* published in 1908 [10]. Cowley was a prolific writer of reviews with dozens of publications critiquing English, French, German and Italian texts. These included several textbooks in geometry, and Cowley particularly recommended those in which analytic geometry and projective geometry were combined in a first year course of study [9, 12, 13]. In writing about teaching at both the high school and college level, Cowley reinforced the value of independent thinking. For instance, in "Some Suggestions on the Technique of Teaching Plane Geometry" she wrote "there is great danger of making the explanations so full and complete that the pupil depends upon his teacher to do all his thinking for him" [11, p. 371]. Instead, Cowley proposed individual work and practical application. Cowley also provided a glimpse into the composition of her descriptive geometry classes where "students ranged from seniors who were honor students majoring in mathematics to sophomores who had nothing beyond solid geometry and plane trigonometry" [11, p. 370]. The diversity of the class composition thus encouraged individual study, made possible by the many interrelated problems and few pre-requisites of descriptive geometry.

Mabel Minerva Young and Marion Elizabeth Stark, two Wellesley professors, also published original research in modern geometry. Young began teaching at Wellesley in 1904 and in 1914 completed her dissertation at Johns Hopkins on "Dupin's Cyclide as a Self-Dual Surface," which appeared two years later in the *American Journal of Mathematics* [42]. The paper focused on self-dual objects, first studied in the context of modern pure geometry during the early nineteenth century. In 1933, Young published further research on "Curves Arising from a Single Infinity of Triangles" [43]. In both articles, Young employed projective, analytic and group theoretic methods and emphasized the potential of her research.

> Almost any notable point or line, however, selected for investigation will prove rewarding and may be trusted to present most stimulating questions of theory for consideration. The writer has been interested chiefly in the projective properties of the figure. Free use has been made of theorems of elementary geometry which describe the special points and lines

> discussed but the curves arising from the motion of these points and lines have been derived by projective methods. They are novel only in that they are simple, familiar forms seen in unfamiliar relationships. The entire configuration has moreover a practical importance in that it offers an easily constructed group of projectively related forms which may to advantage be used for the discussion and illustration of a wide variety of geometric theorems [43, p. 196].

Thus students with some knowledge of modern pure or analytic geometry could follow Young's reasoning and determine their own "stimulating questions of theory."

Stark taught Descriptive Geometry at Wellesley from 1919 through the 1940s. She earned her PhD at the University of Chicago on the calculus of variations, but her subsequent writings focused on geometry and pedagogy. In particular, she published an article synthesizing nineteenth-century contributions to "constructions with limited means" – that is, rigorously constructing geometric figures either with the compass alone or the ruler alone [38]. Stark seems to have continued interest in this topic, later translating and publishing Jakob Steiner's text on the geometry of the ruler, *Geometrical Constructions with a Ruler, Given a Fixed Circle with its Center* [39]. Stark promoted this domain as accessible to a wide audience writing, "the preceding examples give only a small sample of very easy constructions carried out with limited means. It is hoped that they will 'taste like more' to some students, who may care to introduce this type of work to friends at Mathematics Club meetings" [38, p. 479].

Clara Bacon, faculty at Goucher College, began her mathematical research in the field of planar geometry with a master's thesis from the University of Chicago on "The Determination and Investigation of the Real Chords of Two Conics which Intersect in Fewer than Four Real Points" in 1904. Though her thesis was never published, her 1911 PhD dissertation, "The Cartesian Oval and the Elliptic Functions ρ and σ" also included references to results from modern pure geometry and appeared in the *American Journal of Mathematics* in 1913 [1].

The research publications of some faculty suggest that projective geometry remained an open field of study, often comprehensible to undergraduate students, in which women were making notable contributions. In fact, thirty-eight percent of women earning PhDs between 1886 and 1940 wrote their mathematics dissertations on geometry [17]. Certainly, faculty research interests shaped the undergraduate curriculum they taught.

Other faculty publications on mathematics pedagogy shed additional light on the teaching of projective geometry. Two authors stand out in particular for their attention to the relationship between women and mathematics.

Emilie Martin taught an ambiguously titled course, Selected Topics in Geometry, at Mount Holyoke College. She had earned her PhD at Bryn Mawr in finite group theory, studying under Scott and James Harkness. In 1917, she published "Discussions Relating to Required Mathematics for Women Students" in the *American Mathematical Monthly*. In this article, Martin spoke out against those who claimed that women learned enough mathematics in high school "for all practical purposes" or declared "'one does not think so much of a failure in mathematics for a girl'" [20].

Rather, Martin proposed that "a student needs to develop her reasoning powers, and freshman mathematics gives her the best field for practice." In particular, Martin offered three potential benefits for women students in studying mathematics. For women who had no intent of working after college, mathematics generally provided an opportunity to develop "logical reasoning." Martin recognized the stereotype that these skills might be lacking in women and claimed that the testable and law-bound validity of mathematical conclusions particularly served female students prone to be swayed by "bias" and "personality." For those who intended to become teachers, Martin recommended mathematics far beyond what was taught in high school, noting that similar course titles did not indicate comparable content between the high school and college level. Finally, Martin countered the argument that students might take other sciences instead of mathematics, as many sciences required quantitative prerequisites. Though Martin acknowledged the existence of non-mathematical sciences, she noted that a lack of mathematics training severely limited the scope of future contributions.

> These fields may be wide and they may be fertile, but by permitting this limitation women are denying to themselves the equality of opportunity with men that has been won for them at such a cost by the pioneers in the struggle for the right of women to share in the higher education[20, p. 398].

Several years later, Martin wrote "Some Varieties of Space" for *The Mathematics Teacher*, demonstrating her claim for the vast difference between high school and college mathematics. She surveyed the varieties of projective, non-Euclidean and *n*-dimensional geometries that might be pursued by the curious student as well as the philosophical questions raised by so many varieties of space. Each of these geometries went beyond the high school curriculum and thus served to prove part of Martin's earlier argument in favor of required college mathematics for women.

In 1918, while Helen A. Merrill served as the department chair at Wellesley, she addressed an audience of fellow educators in a piece on why students fail in mathematics [21]. Like Martin, Merrill criticized the state of high school mathematics education, remarking that "I have been told by some few students that never until they entered college had they been taught by anyone who showed any enthusiasm for the subject" [21, p. 49]. Merrill called for better teachers of mathematics with a deeper knowledge of the subject. Merrill's article is intended for all students, but she offered particular commentary about "girls" who were often excused from learning mathematics.

> I often marvel, not that some fail, but that so large a proportion succeed, when fathers and mothers say to me: "It seems such a pity for girls to have to waste their time on mathematics. It is always hard for them, and why should they be obliged to study it?" And then they often add "It isn't as if my daughter would ever have to earn her own living," their theory evidently being that the only possible reason why a girl should study mathematics is in order to teach it to others, who will have no mortal use for it except to teach it to other poor victims, etc. [21, p. 52].

Merrill suggested that mathematics might be learned for its own sake or for application to some other domain of knowledge. In her capacity as department chair that year, Merrill explained to the president of Wellesley that the department faced “an unusual number of requests for graduates to fill positions in teaching, in insurance and actuarial work, in electrical companies, in drafting, etc.” [22]. This description of varying possible professions reinforces Merrill’s suggestion that women could learn mathematics for a variety of purposes. United States involvement in World War I could also be a factor here in connection to possible applications.

With these expectations, Merrill called for colleges to teach mathematics that was not “too formal, too theoretical, too removed from everyday use” [21, p. 53]. Though not mentioning any particular course, Merrill may well have had synthetic geometry in mind. In fact, when Wellesley hosted the Sixth Summer Meeting of the Mathematical Association of America, Merrill spoke on “Synthetic projective methods of generating cubic and quartic curves” which was described as “embodying a method which has proved especially interesting even to first year students” [5, p. 356]. Merrill seems to have applied her own advice in her courses on pure synthetic geometry.

Though she never published research articles, course catalogs indicate that Harriet Cobb was particularly devoted to teaching projective geometry at Smith. By 1913 Cobb was a full professor, though she only held a master’s degree. She was the only professor to teach modern pure geometry at Smith College. In the academic year 1920/1921, Cobb took a leave of absence, which explains why Descriptive Geometry, Projective Geometry, and Projective Geometries with Especial Reference to Imaginaries were not offered. That year Cobb had travelled to Wang-Su, China to work with St. Hilda’s School in order “to standardize work in mathematics for Chinese women” [6]. She later described the difficulties in teaching geometry to students who strongly valued memorization and recitation.

> But I found that first “backing them through the proofs” gave most of them the clue, and they said, ‘That new kind of studying is great fun after you know what it is driving at.’ They are slower than our girls and about four years older than Americans in the same grade. But they are in general more serious students, and some of them learned to do excellent work on original proofs [6].

Cobb did not elaborate what she meant by backing through proofs, nor whether this was a pedagogical device employed in her regular classroom.

This cursory overview of faculty activities underscores several motivations for teaching modern pure geometry at women’s colleges. Certainly, as observed by Bussey and Simons, many mathematics majors at women’s colleges went on to teach mathematics, and modern pure geometry served as a means to understanding elementary geometry. However, as Merrill pointed out, the pervasive stereotype of women as teachers could also obstruct future opportunities in mathematical research. Faculty demonstrated the potential for students to engage in original research both through publishing findings that could be understood by a student audience and through structuring classroom learning around individual, self-directed problem solving.

Perhaps most importantly, modern pure geometry appeared as a subject of intrinsic interest. The Committee of Ten in 1892 had promised that synthetic projective geometry could deliver the beauty and esthetic qualities of higher mathematics. In their publications, mathematics faculty also upheld this style of geometry as an example of logical consistency and an alternative to typical school mathematics. Notably, preparing future teachers does not appear to be a major theme in the writings of the college faculty who taught modern pure geometry.

Mathematics faculty advocated for accessible and rigorous mathematics education at women's colleges, and posited that certain kinds of geometry could satisfy these aims. Yet there was no fixed curriculum nor even course title for what kind of modern pure geometry might be taught. In the following section, a study of course catalog descriptions, department reviews, lecture notes and textbooks will reveal some of the ways in which course contents met faculty expectations.

17.4 Course Contents

Most course catalogs contained only the information summarized in our appendix, with a few revealing exceptions. The course on Projective Geometry at Mount Holyoke and the course on Descriptive Geometry at Smith both used Reye's *Geometry of Position*. In the Vassar 1913/1914 catalog the course on Synthetic Projective Geometry included an informative description.

> The course includes the essential topics of elementary projective geometry, developing systematically all the principal theorems on conic sections and ruled surfaces of the second degree. This course is particularly useful to those intending to teach geometry [70].

This was the only mathematics course recommended to future teachers at Vassar in that year, but in 1916 the last sentence was replaced with a recommendation as a supplement to courses in curve tracing and analytic geometry. Instead, the course entitled Modern Methods of Analytic Geometry was described as "useful to those intending to teach or to pursue advanced studies" [93]. This change persisted through 1924, perhaps reflecting a relative decline in importance for purely geometric methods.

The other detailed course descriptions come from Wellesley. A course on Modern Synthetic Geometry consisted of:

> Metrical and projective properties of plane and sheaf forms of the first and second orders; the anharmonic ratio; harmonic forms; the method of inversion; involution; collineation; the law of duality; theory of poles and polars; reciprocation; space forms and surfaces of the second order. Given by lectures and references, with constant practice in the solution of geometrical problems [80].

Beginning in 1918, students could also take a course in Descriptive Geometry, though, as noted above, both courses could not be counted toward the degree. In contrast, descriptive geometry employed projection, but the description appears far less theoretical.

> The theory and practice of the representation of geometric figures. The use of two or more planes of projection in representing lines, surfaces and solids; intersection of surfaces; shades and shadows; the elements of perspective. Two lectures each week, with two additional consecutive periods for drawing under supervision [85].

In the department report that year, then chair Helen Merrill explained that the current "demand for draftsmen has led to the introduction of a course in Descriptive Geometry in 1918–19, which should fit our students not merely for the purely mechanical and often elementary side of the work, but for more difficult and advanced work with which it is hoped that positions now opening may lead" [22, p. 4]. Pure geometry courses fulfilled practical societal expectations, while maintaining high standards for students.

Since modern pure geometry was usually an independent course, this enabled a flexibility that might not have been as available for a course in a predetermined sequence. Catalog descriptions listed what was taught, but to better understand how modern pure geometry was taught requires consulting available lecture notes and textbooks. These documents include Von Staudt's *Beiträge der Geometrie* (Smith), Reye's *Geometry of Position* (Mount Holyoke and Smith); *Elements of Projective Geometry* cowritten by George Herbert Ling, George Wentworth, and David Eugene Smith (Hunter); and a set of typed notes on Modern Synthetic Geometry from Ellen Burrell at Wellesley. Despite Bussey's complaint about a lack of available textbooks in English, institutions or faculty had some choice.[7] Accordingly, the choice of text (or choice of not using a textbook at all) would appear to reflect intended goals for the course, and even the four above-mentioned provide a substantial range of approaches and content.

Von Staudt's *Beiträge* (1856–1860) is a three-volume exposition of imaginary elements in geometry. An analysis of its contents would go well beyond the scope of this paper, and the interested reader is directed to Scott's summary [32–34]. Along with Scott's commendations, historian and geometer Julian Lowell Coolidge praised von Staudt's text for his non-metric treatment of imaginaries, but warned that it became "totally unmanageable when it comes to dealing with anything more involved than linear and quadratic forms" [8, p. 104]. As a potential textbook, the *Beiträge* contains no diagrams nor exercises. There were no further editions or translations after the first editions, and, as Scott noted, "von Staudt's presentation is at times obscure, at times tedious; and as he lacks the conciliatory style that does so much to encourage a student, very few have the patience to persevere" [32, p. 307]. These qualities make it a surprising choice of text for an early twentieth-century American college course, and reinforce the impression that students might choose to learn projective geometry for more philosophical reasons.

Subsequent treatments of modern synthetic geometry adapted and revised von Staudt's text for a wider audience. Reye wrote *Geometrie der Lage* in 1866 as a student-friendly version of von Staudt's text of the same title. In 1898, Thomas Holgate, then a professor at Northwestern University, published a translation of the second edition of Reye in order "to place within easy reach of the English-speaking

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[7] For instance, other available textbooks in modern pure geometry from this period include [15, 16], and [18].

student of pure geometry an elementary and systematic development of modern ideas and methods" [26, p. v]. By 1913, the English translation was out of print [4]. In 1922 the publication of *Elements of Projective Geometry* aimed to fill that lacuna as "a thoroughly usable textbook in projective geometry" [26, p. iii]. The book was based on lecture notes written by Ling, the same notes that had been employed at Hunter College by Simons for at least the past decade. In some modern geometry courses no textbook appears to have been used. Such was the case at Wellesley, where Ellen L. Burrell revised and typed her course notes in 1937 based on courses taught over twenty-years before [3]. She explained the delay in her introduction, which we quote at length to demonstrate her dedication to the task.

> My revision of the notes of what was Course Six in Pure Mathematics, has now been completed. I deeply regret that the work has been so long postponed, that I have been able to do it only by proxy, as it were, having the notes read to me and dictating the copy, making such re-arrangement and changes as I could. I can only hope that the result has included no logical errors. The order of the Sections is almost exactly as when I was giving the course, but the subject matter is not arranged as I would wish in many places.
>
> When College Hall burned, my library and all my notes of every kind were destroyed. The notes I used were those prepared for me during the vacation following the fire, by Alma Bowen '14, and those of Frances Mullinax, '13, who loaned me her class notes. [...] The second part of the notes was written by myself, after the fire, to complete the course as I gave it.

As an unpublished manuscript, Burrell's notes contain almost no diagrams and the second, hand-written part had yet to be organized according to her desired schemata (excerpts from this second part will be designated with section numbers as the pages are unnumbered).

These three pedagogically oriented texts convey the primary possible purposes for teaching modern pure geometry at women's colleges: to create a deeper knowledge of elementary geometry, to develop research techniques and acumen, and to develop mathematical intuition. Content corresponding to these themes will guide the following comparisons. First, we will consider how authors addressed the visual and constructive aspects of geometry. These qualities reinforced the figure-based practices of planar and solid geometry as taught in high schools. Then, to see how modern pure geometry could direct future research, we discuss the fundamental principle of duality presented as a means for practicing proofs and deriving new mathematical knowledge. Finally, contrasting treatments of imaginary elements reflect varying values placed on geometry and geometrical intuition as part of the liberal arts education.

17.4.1 Visualization and Construction

Though geometry was no longer considered the study of figures in space, illustrations and models remained prominent in most elementary geometry classrooms. Not only students relied on the visual aspects of geometry, but also all those who applied geometric constructions. For instance, Reye dedicated his text to providing engineers with a geometric imagination.

> But still the engineer, and everybody else who wishes to become familiar with his ideas, must continually exert his power of imagination [*Vorstellungskraft*] in order actually to see the object intended to be represented by the lines of a drawing which is not at all intelligible to the uninitiated [26, p. xii].

To this end, Reye distinguished his text from that of von Staudt by including numerous figures in the text. When these illustrations could not be provided, especially in the case of three-dimensional figures, Reye required his students exercise their imagination by forming mental images

> Of the knowledge of geometry acquired in the elementary schools, I shall therefore make very little use. On the other hand, a certain skill in producing mental images of geometric forms without pictorial representations would be of great service to you, inasmuch as it will not be practicable for me to illustrate every theorem by diagrams, especially if the theorem refers to a form in space; I shall often be compelled to make demands upon your imagination [26, p. 2].

As well as forming mental pictures, Reye instructed students to read with a pencil and paper in order to graphically solve the problems presented and draw diagrams as described in the text.

Elements of Projective Geometry was quite similar in this respect. Ling, Wentworth, and Smith directed their text at three potential audiences of students, "those who expect to proceed to the domain of higher mathematics, those who are intending to take degrees in engineering, and those who look forward to teaching in the secondary schools" [19, p. iii]. The authors frequently advised readers to construct figures following the written procedure and then verify their illustrations with the ones provided in the text. Unlike Reye, the authors provided numerous illustrations of surfaces in three dimensions as well as directions for building string models [19, p. 178]. Exercises for the students that followed each chapter reinforce these strategies.

Though lacking many illustrations, Burrell still described the synthetic method as "observing forms and figures" [3, p. ii]. She also offered practical applications at the end of her first section by concluding with a discussion of map making and projections.

> The subject is entered into here chiefly to illustrate the value of the work done so far in these notes from the practical standpoint. Until these various projections and their modifications were invented, maps were mere sketches without accuracy in any respect [3, p. 86]

Following this nod to practical applications, Burrell's notes became increasingly abstract and removed from representation. In her discussion of objects in space she observed that "all restrictions made by visual notions are now removed from the perspective idea" [3, Section 348].

In the plane the introduction of modern methods could be connected to elementary geometry by the use of constructions and diagrams. At the beginning of their texts, each of the above authors introduced familiar ruler and compass constructions and defined new objects in terms of points, lines, and planes. The texts diverged in the authors' treatments of spatial figures and suggest an extended continuum from model building to mental pictures to completely abstract deductions.[8]

17.4.2 The Principle of Duality

Visual figures might remind college students of high school geometry, but most of modern pure geometry was new and subject-specific, such as the principle of duality. In all three texts duality served to derive new results and to reveal the underlying structure of non-metric geometry. *Elements of Projective Geometry* offered the most condensed definition.

> Corresponding to any figure in space which is made up of or generated by points, lines, and planes there exists a second figure which is made up of or generated by planes, lines, and points, such that to every point, every line, and every plane of the first figure there corresponds respectively a plane, a line, and a point of the second figure, and such that to every proposition which relates to points, lines, and planes of the first figure, but which does not essentially involve ideas of measurement, there corresponds a similar proposition regarding the planes, lines and points of the second figure, and these two propositions are either both true or both false [19, p. 13].

The utility of the principle of duality was perhaps best shown by examples and each of the three texts employed dual columns to represent this correspondence.[9] By proving propositions on both left and right sides independently, the authors could avoid requiring any justification of duality's validity.

Halfway through his text, Reye used polar reciprocity and second order curves to show how points and lines could be dually related in the plane.

> This and preceding theorems establish the principle of reciprocity (to which I shall return later), at least for the plane, or in general for primitive forms of two dimensions. For, to any plane figure we can construct, by the aid of a curve of the second order, a reciprocal plane figure by determining for every point of the first, its polar, and for every straight line, its pole. For this reason it will be sufficient hereafter if of two reciprocal theorems upon plane figures I demonstrate only one [26, p. 102].

He later extended this principle to include all elementary forms in an "analogous" manner [26, p. 134].

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[8]Mathematics departments prized their collections of models bought from German manufacturers or made by students. For instance, a 1919 history of Mount Holyoke described "a collection of models, of plaster and thread, illustrating quadric surfaces, surfaces of the third and fourth orders, Riemann surfaces and surfaces of complex functions" [37, p. 16]. Presumably some of these, like quadric surfaces, would be useful in higher geometry courses.

[9]Vassar professor Sophia Richardson's textbook *Solid Geometry* also included instances of dual columns and she outlined the concept in a brief note: "In the geometry of the line and plane it happens that so many instances occur of pairs of theorems thus related to each other, that the study of the topic is somewhat simplified by considering in the case of each theorem the theorem derived from it by the interchange of the words line and plane" [27, p. 22].

Burrell's use of duality was more general and referred to objects only defined in modern synthetic geometry.

> The law of duality has been stated in the introduction to be one of the fundamental laws of mathematics. The relations of the fundamental elements under this law, will now be stated.

Point	Straight Line
Straight Line	Point
Range	Flat Pencil
Flat Pencil	Range

> [...] The meaning of the law of duality is–that if we have a theorem on the left we may obtain the theorem on the right by making the interchange as given in this list. Strictly speaking, the law of duality is a fundamental law of the Geometry of Position. All theorems hereafter will have this double statement when possible [3, p. 26].

Burrell promised to fully prove the law of duality, and in the hand-written second-half of her notes provided a justification largely grounded on utility.

> The law of duality is arbitrarily assumed and then systematically used for obtaining correlative figures and correlative theorems in regard to these figures. The result is a complete justification of the law of duality [3, Section 272].

Given the incomplete nature of these notes, it is not clear whether this was the proof she envisioned in her introduction.

The dual form introduced students to writing proofs through simple linguistic substitutions. These derivations feature prominently as exercises throughout the two textbooks. Reye cited several "double theorems" in dual columns and encouraged his students to follow his example. "I strongly urge you to deduce for yourselves, from the one half of each of these, the other reciprocal half" [26, p. 27]. That the application of duality could lead to publishable new results is demonstrated by Mabel Young's paper on self-dual surfaces discussed in Sect. 17.3 above.

17.4.3 Imaginary Elements

While the three texts had very similar approaches to duality, their exposition of imaginary elements diverged. In *Elements of Projective Geometry* imaginary values only appear briefly as solutions to algebraic equations. These were then dismissed as not concerning "the anharmonic ratio of four real collinear points" [19, p. 27]. Reye limited his presentation to real values for the majority of his text, and only introduced imaginary elements in lesson XIV in the context of problem solving.

> Problems of the second order have given the first occasion for the introduction into synthetic geometry of 'imaginary' points, lines, and planes; and, to have founded the purely geometric theory of imaginary elements and to have brought it to a high degree of completeness is undoubtedly one of the greatest services which Von Staudt has rendered. From the nature of the subject this theory must, in synthetic as well as in analytical geometry, give up all

> claim upon the powers of intuition; consequently, I shall confine myself at this point to the presentation of only the first principles of the theory of geometric imaginaries [26, p. 184].

He then defined self-corresponding elements as "'imaginary' whenever they do not really appear." This then removed any exceptions to the theorem that a second order curve and a straight line always intersect in exactly two points. Following Reye's definition, when the curve and line do not "appear" to intersect, the two points of intersection are conjugate imaginary points. Reye proceeded by demonstrating that conjugate imaginary points are collinear on a real straight line. He hinted at further generalizations, but did not go "into the matter more minutely." [10]

With less of a focus on intuition and visualization, Burrell listed "the imaginary" as the sixth fundamental concept of geometry of position.

> This concept so long a stumbling block to mathematicians serves, in this work, to complete statements and avoid exceptions. It completes the number system of algebra and has long been accepted as indispensable [3, pp. 2–3].

Following von Staudt, Burrell defined conjugate imaginary double points independently of sense perception. When two projective ranges are superposed, but "no pair of real points coincide" then the "double points" are considered to be conjugate imaginary double points. Nevertheless, Burrell acknowledged that constructions remain limited to real objects, such as in her definition of inversion with respect to an imaginary circle: "Inversion may, in general, be real or imaginary, but in actual construction it is taken as real" [3, p. 72]. Burrell proceeded to generalize imaginary elements to higher dimensions in her hand-written notes. Her course thus seems more abstract and advanced, requiring both differential and integral calculus as pre-requisites. With references to Plücker, Chasles, von Staudt and Hilbert, Burrell expected her students to be familiar with a wide range of geometry practices.

In teaching a subject outside of the major sequence, instructors could exercise discretion with respect to content. Indeed these variations could reflect department goals. At Hunter, a college aimed almost exclusively at preparing future teachers, the emphasis lay on the visual, intuitive, and constructively verifiable. By contrast, though many graduates of elite private women's colleges went into education, modern geometry appears to have been taught as a more abstract and theoretical subject. Regardless of the institution, instructors agreed that courses for women should be as rigorous as those at comparable co-ed or all male institutions. As described in a 1919 history of Mount Holyoke,

> Mary Lyon [the founder of Mount Holyoke] tolerated no comfortable delusions regarding the limitations of the feminine mind. "There is no reason why ladies should not faithfully pursue such subjects (Latin and Mathematics) as well as gentlemen" [37, p. 12].

This equality was not a universally acknowledged truth among mathematicians in this time period, as is shown, for example in William Fogg Osgood's address on course design in 1918 where he noted "that teachers need continually to adapt their

[10] In the translator's introduction, Holgate quoted H.J.S. Smith with approval as stating "All attempts to construct imaginaries have been wholly abandoned in pure geometry" [26, p. viii].

methods to the various conditions, for example, that women students are not as a class vitally interested in the problems of physics" [5, p. 356].

17.5 Conclusion

Modern pure geometry as taught between 1913 and 1923 confirms William Henry Bussey's claim that such courses regularly featured in women's colleges. However, while Bussey lamented a lack of uniformity, the wide scope of modern geometry also meant that it could be adapted to a range of students. At women's colleges, the primary audience appears to have been future teachers, which coincides with the common expectations of mathematics graduates at these institutions. The following description from Mount Holyoke might apply equally well at any women's college in this period.

> Since many of those who make mathematics a major expect to teach in the secondary schools, the attempt is made to give them an outlook such that they will be able to see the elementary subjects from the standpoint of their relations with the higher mathematics and with the needs of the world [37, p. 17].

Yet, as course contents show, modern pure geometry also prepared future mathematicians, engineers, draftsmen, and logical thinkers. Further, most of these higher geometry courses at women's colleges remained accessible to students simply interested in furthering mathematical thinking. Though we do not know the enrollment numbers, the persistence of these courses suggests their popularity despite their elective status.[11]

Because non-metric geometry could be concrete and intuitive, relatively free of prerequisites but possess deep mathematical insight, it appeared to solve many of the problems facing mathematics educators at women's colleges. In particular, faculty publications pointed to students struggling with abstract mathematics, poorly trained school teachers, and the false belief that school mathematics accurately represented the entire discipline. As the twentieth century progressed, the rise of axiomatic and non-Euclidean geometry, the decline of projective geometry as a research subject,[12] and the development of computer graphics led to changes in the mathematics curriculum. This paper has shown how modern pure geometry served the faculty and students of women's colleges. The story of its disappearance from these venues would be the subject of another study.

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[11] By contrast, some elective courses were dropped or offered only infrequently.

[12] For a pessimistic or resigned view on this see, respectively [2] or [7].

Appendix: Summaries of Course Catalogs

This appendix was constructed with reference to [44–99].

College	Year	Course	Instructor	Sequence	Credits
Vassar	1913/1914	M. Synthetic Projective Geometry	Richardson	Prerequisite: Course A [Analytic Geometry]	Second semester [3].
	1914/1915	M. Synthetic Projective Geometry	Richardson	Prerequisite: Course A [Analytic Geometry]	Second semester [3].
	1915/1916	M. Synthetic Projective Geometry	Richardson	Prerequisite: Course A [Analytic Geometry]	Second semester [3].
	1916/1917	M. Synthetic Projective Geometry	White	Prerequisite: Course A [Analytic Geometry]. This course is valuable as a supplement to courses I (Curve Tracing) and J (Analytic Geometry of Three Dimensions).	Second semester [3].
	1917/1918	M. Synthetic Projective Geometry	White	Prerequisite: 11. This course is valuable as a supplement to 1 (plane trigonometry, with logarithms), 11 (analytic geometry) and 15 (analytic geometry of three dimensions).	Second semester [3].
	1918/1919	26. Synthetic Projective Geometry. Second Semester.	White	Prerequisite: 11. This course is valuable as a supplement to 1 (plane trigonometry, with logarithms), 11 (analytic geometry) and 15 (analytic geometry of three dimensions).	Second semester [3].
	1919/1920	19 and 20. Introduction to Descriptive Geometry and Mechanical Drawing	Cowley	1. Plane trigonometry with Logarithms and 2. Solid Spherical Geometry	First semester [1], Second semester [1]. Two hours in the classroom, with very little preparation, to be counted as one hour.

		26. Synthetic Projective Geometry	White	Prerequisite: 11. This course is valuable as a supplement to 1 (plane trigonometry, with logarithms), 11 (analytic geometry) and 15 (analytic geometry of three dimensions).	Second semester [3].
	1920/1921	19 and 20. Introduction to Descriptive Geometry and Mechanical Drawing	Cowley	1. Plane trigonometry with Logarithms and 2. Solid Spherical Geometry	First semester [3], Second semester [3].
		26. Synthetic Projective Geometry	White	Prerequisite: 11. This course is valuable as a supplement to 1 (plane trigonometry, with logarithms), 11 (analytic geometry) and 15 (analytic geometry of three dimensions).	Second semester [3].
	1921/1922	19 and 20. Introduction to Descriptive Geometry and Mechanical Drawing	Cowley	1. Plane trigonometry with Logarithms and 2. Solid Spherical Geometry	First semester [3], Second semester [3].
		26. Synthetic Projective Geometry	White	Prerequisite: 11. This course is valuable as a supplement to 1 (plane trigonometry, with logarithms), 11 (analytic geometry) and 15 (analytic geometry of three dimensions).	Second semester [3].
	1922/1923	19 and 20. Introduction to Descriptive Geometry and Mechanical Drawing	Cowley	1. Plane trigonometry with Logarithms and 2. Solid Spherical Geometry	First semester [3], Second semester [3].
		26. Synthetic Projective Geometry	White	Prerequisite: 11. This course is valuable as a supplement to 1 (plane trigonometry, with logarithms), 11 (analytic geometry) and 15 (analytic geometry of three dimensions).	Second semester [3].

(continued)

College	Year	Course	Instructor	Sequence	Credits
Mount Holyoke	1913/1914	Projective Geometry	Smith	Open to juniors	First and second semester, three hours
	1914/1915	8 and 9. Projective Geometry	Doak	Open to juniors	First and second semesters, each three hours
	1915/1916	8 and 9. Projective Geometry	Doak	Open to juniors	First and second semesters, each three hours
	1916/1917	8 and 9. Projective Geometry	Doak	Open to juniors	First and second semesters, each three hours
	1917/1918	8 and 9. Projective Geometry	Doak	Open to juniors	First and second semesters, each three hours
	1918/1919	8 and 9. Projective Geometry	Smith	Open to juniors	First and second semesters, each three hours
	1918/1919	10. Selected Topics in Geometry	Martin	Prerequisite: Differential and Integral Calculus, Introduction to the Calculus, Analytical Geometry, Solid and Spherical Geometry or College Algebra and Plane Trigonometry	First semester, three hours
	1919/1920	8 and 9. Projective Geometry	Smith	Open to juniors	First and second semesters, each three hours
	1919/1920	10. Selected Topics in Geometry	Martin	Prerequisite: Differential and Integral Calculus, Introduction to the Calculus, Analytical Geometry, Solid and Spherical Geometry or College Algebra and Plane Trigonometry	First semester, three hours
	1920/1921	8 and 9. Projective Geometry	Smith	Open to juniors	First and second semesters, each three hours
	1921/1922	8 and 9. Projective Geometry	Doak	Open to juniors	First and second semesters, each three hours

Smith	1913/1914	3. Descriptive Geometry	Cobb	For Juniors.	Three hours, through the year.
	1914/1915	3. Descriptive Geometry	Cobb	For Juniors and Seniors	Three hours, through the year.
	1915/1916	3. Descriptive Geometry	Cobb	For Juniors and Seniors	Three hours, through the year.
	1916/1917	32b. Descriptive Geometry	Cobb	none	Three hours, second semester.
		37. Projective Geometry	Cobb	It is recommended that this course be preceded by 32b.	Three hours, through the year.
	1917/1918	32b. Descriptive Geometry	Cobb	none	Three hours, second semester.
		37. Projective Geometry	Cobb	none	Three hours, through the year.
		32a. Descriptive Geometry	Cobb	none	Three hours, first semester
		37. Projective Geometry	Cobb	none	Three hours, through the year.
		42. Projective Geometry with Especial Reference to Imaginaries. Beiträge zur Geometrie der Lage by K. von Staudt	Cobb	none	no information
	1919/1920	32b. Descriptive Geometry	Cobb	none	Three hours, second semester.
		37. Projective Geometry	Cobb	none	Three hours, through the year.
		42. Projective Geometry with Especial Reference to Imaginaries. Beiträge zur Geometrie der Lage by K. von Staudt	Cobb	none	no information
	1920/1921	all courses omitted			
	1921/1922	32b. Descriptive Geometry	Cobb	none	Three hours, second semester.
		37. Projective Geometry	Cobb	none	Three hours, through the year.
		42. Projective Geometry with Especial Reference to Imaginaries. Beiträge zur Geometrie der Lage by K. von Staudt	Cobb	none	no information
	1922/1923	32a. Descriptive Geometry	Cobb	none	Three hours, second semester.
		37. Projective Geometry	Cobb	none	Three hours, through the year.
		42. Projective Geometry with Especial Reference to Imaginaries. Beiträge zur Geometrie der Lage by K. von Staudt	Cobb	none	no information

(continued)

College	Year	Course	Instructor	Sequence	Credits
Wellesley	1913/1914	6. Modern Synthetic Geometry	Burrell	Open to students who have completed or are taking course 3 [Differential and Integral Calculus].	Three hours a week for a year.
	1914/1915	6. Modern Synthetic Geometry	Chandler	Open to students who have completed or are taking course 3 [Differential and Integral Calculus].	Three hours a week for a year.
	1915/1916	none			
	1916/1917	6. Modern Synthetic Geometry	Merrill	Open to students who have completed or are taking course 3 [Differential and Integral Calculus].	Three hours a week for a year.
	1917/1918	6. Modern Synthetic Geometry	Merrill	Open to students who have completed or are taking course 3 [Differential and Integral Calculus].	Three hours a week for a year.
	1918/1919	17. Descriptive Geometry	Merrill	Open to students who have completed or are taking course 3 [Differential and Integral Calculus].	Three hours a week for a year.
	1919/1920	6. Modern Synthetic Geometry	Merrill	Open to students who have completed or are taking course 3 [Differential and Integral Calculus].	Three hours a week for a year.
		17. Descriptive Geometry	Merrill	Open to students who have completed or are taking course 3 [Differential and Integral Calculus].	Three hours a week for a year.
	1920/1921	206. Descriptive Geometry	Merrill	Open to students who are taking a three-hour elective course in Mathematics.	One hour a week for a year with one laboratory period.
		306. Modern Synthetic Geometry	Merrill	Open to students who have completed or are taking course 3 [Differential and Integral Calculus].	Three hours a week for a year.
	1921/1922	206. Descriptive Geometry	Merrill	Open to students who are taking a three-hour elective course in Mathematics.	One hour a week for a year with one laboratory period.
		306. Modern Synthetic Geometry	Merrill	Open to students who have completed course 202 [Differential and Integral Calculus] or 301 [Calculus and Its Applications]	Three hours a week for a year.
	1922/1923	206. Descriptive Geometry	Stark	Open to students who are taking a three-hour elective course in Mathematics.	One hour a week for a year with one laboratory period.
		306. Modern Synthetic Geometry	Young	Open to students who have completed course 202 [Differential and Integral Calculus] or 301 [Calculus and Its Applications]	Three hours a week for a year.

Bryn Mawr	1914/1915	Ib. Lectures on Modern Pure Geometry	Scott	Post-Major	Two hours a week throughout the year
	1915/1916	none			
	1916/1917	Ib. Lectures on Modern Pure Geometry	Scott	Post-Major	Two hours a week throughout the year
	1917/1918	Ib. Lectures on Modern Pure Geometry	Scott	Post-Major	Two hours a week throughout the year
	1918/1919	none			
	1919/1920	Lectures on Modern Pure Geometry	Scott	Post-Major	Two hours a week throughout the year
	1920/1921	none			
	1921/1922	Lectures on Modern Pure Geometry	Scott	Post-Major	Two hours a week throughout the year
	1922/1923	none			

(continued)

College	Year	Course	Instructor	Sequence	Credits
New York Normal School	1913/1914	26. Projective Geometry	Simons	Prerequisite: Course 15 [Plane Analytic Geometry]	3 periods, one half-year; 3 semi-annual credits.
	1914/1915	35. Projective Geometry	Simons	Prerequisite: Course 15 [Plane and Solid Analytic Geometry]	3 periods, one half-year; 3 semi-annual credits.
	1915/1916	35. Projective Geometry	none listed	Prerequisite: Course 24 [Plane Analytic Geometry]	3 periods, one half-year; 3 semi-annual credits.
	1916/1917	35. Projective Geometry	none listed	Prerequisite: Course 24 [Plane Analytic Geometry]	3 periods, one half-year; 3 semi-annual credits.
	1917/1918	35. Projective Geometry	none listed	Prerequisite: Course 24 [Plane Analytic Geometry]	3 periods, one half-year; 3 semi-annual credits.
	1918/1919	35. Projective Geometry	none listed	Prerequisite: Course 24 [Plane Analytic Geometry]	3 periods, one half-year; 3 semi-annual credits.
	1919/1920	35. Projective Geometry	none listed	Prerequisite: Course 24 [Plane Analytic Geometry]	3 periods, one half-year; 3 semi-annual credits.
	1920/1921	35. Projective Geometry	none listed	Prerequisite: Course 24 [Plane Analytic Geometry]	3 periods, one half-year; 3 semi-annual credits.
	1921/1922	35. Projective Geometry	none listed	Prerequisite: Course 24 [Plane Analytic Geometry]	May be given only in the spring term. 3 periods, one half-year; 3 semi-annual credits.
	1922/1923	35. Synthetic Projective Geometry	none listed	Prerequisite: Course 24 [Plane Analytic Geometry]	3 periods, one half-year; 3 semi-annual credits.

Goucher	1915/1916	8. Pure Projective Geometry	Bacon	Prerequisite, Course 4 [Plane Analytic Geometry]	Three hours, first semester.
	1918/1919	19. Pure Projective Geometry	Bacon	Prerequisite, Courses 11-12 [Plane Analytic Geometry]	Three hours, first semester.
	1919/1920	19. Pure Projective Geometry	Bacon	Prerequisite, Courses 11-12 [Plane Analytic Geometry]	Three hours, first semester.
	1920/1921	19. Pure Projective Geometry	Bacon	Prerequisite, Courses 11-12 [Plane Analytic Geometry]	Three hours, first semester.
	1921/1922	19. Pure Projective Geometry	Bacon	Prerequisite, Courses 11-12 [Plane Analytic Geometry]	Three hours, first semester.
	1922/1923	19. Pure Projective Geometry	Bacon	Prerequisite, Courses 13-14 [Differential and Integral Calculus]	Three hours, first semester.

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Chapter 18
Using Humor to Combat Inequities

Sue Geller

Abstract How to promote peace between groups of people remains an open question, and sometimes we seem very far from a solution. Eliminating large-scale societal injustices—so-called macro-inequities—is beyond the capacity of a small group of people. But improving the climate in a smaller community is a more tractable goal. The Mathematical Association of America (MAA) Committee on the Participation of Women used the word "micro-inequities" to refer to unfair and/or offensive behaviors that individually may seem too small to be harmful. These behaviors may even seem humorous when recounted in a safe environment. Nonetheless, these occurred so frequently in the mathematical workplace that they felt hostile to the targeted women. Indeed, women felt unappreciated, helpless, and angry. Skits portraying micro-inequities were presented at the Winter and Summer Joint Math Meetings in the years 1990–1994. The goals were to increase awareness of micro-inequities and change some of those unfair behaviors. The skits illustrated true examples of micro-inequities, many but not all perpetrated by males on females, all taking place in the mathematics world. Some skits showed injustices that passed unnoticed by any except the recipient. Other skits showed how thoughtful observers found ways to challenge the behavior and support the recipient. This article will explain the origin of the skits, provide examples, and describe some of the results.

Keywords Micro-inequity • Humor • Social climate • Skits

18.1 Introduction

The good news: The climate in academic mathematics has changed for the better over the last 50 years. Overt sexual harassment is now a rarity rather than common. Many mathematics departments, including research departments, now have 10% or more tenure-track females, which is an improvement although not quite a critical mass of women in many places. Before the 1990s, a maximum of one female total

S. Geller (✉)
Texas A&M University, College Station, TX, USA
e-mail: geller@math.tamu.edu

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per mathematics department, especially a research mathematics department, was common. As a result the burden is no longer on the solitary woman to represent her gender on every committee. Once on a committee, a woman is now more likely to be heard rather than consigned to invisibility and inaudibility. Women now run graduate programs, chair departments, and do other administrivia, including administrative roles, which had been solely a male prerogative.

The bad news: Since we are still human and the product of our upbringings, unconscious biases can still make life uncomfortable not only for women, but also for people from different ethnic or national backgrounds. In large meetings, women sometimes are still treated as invisible or inaudible. Men may talk over them or even accept praise for repeating suggestions ignored when previously made by women.

It was because of the small statements made out of unconscious biases or habit that the term "micro-inequity" was adopted by mathematicians in 1989 (see 18.2 below). They happen to everyone, but especially to women, and often the same example happens repeatedly. They are just as real today as they were over 27 years ago. They are not limited to the mathematical community; they can and do happen to women in almost every community in which women are a minority. However minor-seeming the injustice, when they happen repeatedly, they can eat at our self esteem, or cause us to be unhappy or even angry. Fortunately, many of these injustices create funny stories to tell. We made use of this humor to help to increase awareness and to change our micro-climate. What follows is the history of our actions, including details of how we (partly) accomplished our goals. Spoiler alert: The results were often positive and sometimes funny and sad at the same time.

18.2 History

In summer 1989, the Joint Mathematics Meetings (JMM) were held at the University of Colorado Boulder. (This was before there was a MathFest. Back then there were the Winter JMM and the Summer JMM which included the AMS, AWM, MAA, and other societies.) Many of us came a bit early to enjoy various events offered as vacation entertainment before the meetings. The Mathematical Association of America (MAA) Committee on Participation of Women met twice that summer, which ended up being a good thing. During the first meeting, we spent some time venting about things that had happened to us so far, but ended up laughing at the telling. We then made a serious evaluation of the panels the committee had put on at the various JMMs in order to decide what topic to cover on our next panel. By the meeting at the end of the week, the first thing the chair, Pat Kenshaft, told us was that the committee's usual panel had been assigned to be at 7:30 pm on Friday night in San Francisco for the winter JMM. Everyone was appalled. How could we interest mathematicians to come to a serious panel on Friday night and in San Francisco of all places? How could we continue to try to make a difference in the climate for women? Someone observed that what we had been talking about in our first meeting would be a good light-hearted way to get some points across and that people might be willing to come to see skits. Thus a new mode of consciousness raising was introduced into the math community. We decided that all the skits should be true with only the names changed to protect the guilty (apologies to Jack Webb of Dragnet fame). I agreed to be the skitwright; Pat and I agreed to produce them together. It seemed like a great idea. I chose five vignettes we had heard at Boulder, including one with Pat as perpetrator, and wrote up dialogs.

We got to San Francisco, and Pat and I realized that we needed actors, preferably ones with enough mathematical gravitas to provide weight and credibility to the skits. Larry Corwin (1943–1992) had already agreed to be an actor as had some women, but we needed many more. So Pat and I worked the Exhibition Hall asking people to help us. We were amazed at the number of favorable responses. Some of our recruits were famous mathematicians whose departments included no women faculty at that time, but who thought the skits would be fun. Without their eminence, I doubt we would have been taken as seriously as we were.

Rehearsals and performances were fun. The performers changed some of the lines for the better. We were flexible. For example, one of the skits was set on a bus which took a group to see some of the Rockies, so the people in the chairs were supposed to bounce to represent the movement of the bus. One gentleman had bad knees and couldn't bounce. So he got to play the eminent mathematician and the narrator commented that the reason the eminent mathematician's seat didn't bounce was that he had an endowed chair.

Doing skits that Friday night was apt since there were marches which turned to small riots against the first Gulf War, Desert Storm, in San Francisco that night. We felt that we were providing a safe haven from the demonstrations and some humor to lighten the darkness of the war.

The following skit portrays a micro-inequity which still happens today, not just in the mathematical community, but in others as well.

At the Cafeteria

Announcer: We are in the cafeteria in the dorm area. A husband and wife are eating dinner together when another couple comes to their table.

Dr. X: (*the standing man*) Hi, I'm Dr. X and this is my wife Joanne. May we join you?

Dr. Y: (*the seated woman*) Certainly. I'm Dr. Y and this is my husband Mr. John Y. He's a lawyer.

Throughout then ensuing dialog Dr. X positions himself so that he is looking at Mr. Y. and has his shoulder to Dr. Y and to Mrs. X.

Dr. X: Say, John, where do you teach?
John: I'm a lawyer; my wife is a mathematician.
Dr. X: What's your field of research, John? Algebra? Analysis? Applied math?
John: I'm a lawyer; my wife is a mathematician.
Dr. Y: I'm in PDE's. What do you do?
Dr. X: Say, John, do you get to teach many graduate classes?

John: (*with increasing irritation*) I'm a lawyer; my wife is a mathematician. Why don't you ask her?

Dr. X: I like teaching big, lower level classes occasionally, but I prefer the upper division and graduate students. How many classes do you teach each semester, John?

John: (*with great exasperation*) I'm a lawyer; my wife is a mathematician. Please talk to her!

Dr. X: Say, do you wear a suit to class, a jacket and tie, or just a sport shirt and slacks?

Announcer: We pull the curtain over this scene. Suffice it to say that Dr. X took a long time to figure out that Mr. Y was not a mathematician and Dr. Y was.

Curtain

At the conclusion of our presentation, it was requested that we repeat the skits at the summer JMM, so that more people could see them. This pattern became our customary mode of operation—new skits in January repeated in the summer. Through the year people would send me stories of what had happened to them. As time went on, men would send me stories of micro-inequities "they thoughtlessly committed" and asked to play themselves by name and, of course, they did.

We had one scary night. I had written a skit about something which happened to me, and the perpetrator showed up and sat in the front row. I whispered to Pat what had happened, and we decided to proceed as if he weren't present. We were very surprised when he not only laughed during that skit but also came up afterwards and said he was glad that he didn't do any of the things portrayed. It was hard for all of us not to burst out laughing but we managed. It did demonstrate how clueless people can be as the perpetrator had done this to me many times. In fact, I had used the skit as a way of getting my anger out and a bit of revenge to boot. The joke was on me that night, but this was just one of the funny and sad results alluded to in the introduction.

At the request of many people, we started having small group discussions after the skits so people could process, add ideas or in some way enrich their experience of the evening. We added a training session for discussion leaders. Although this meant added work for Pat and me, it was worthwhile. The discussions were rich and many friendships started in them. It also helped people bring back what they learned to their home institutions.

The last set of skits I wrote were for the 1993 winter JMM and are dedicated to Larry Corwin, whose untimely death we all mourned. Not only was he a great mathematician, but he was also a wonderful man without whom our skit night might have been a one time event. For all of my skits, see http://www.math.tamu.edu/~geller/skits.pdf.

18.3 Results

Our skits were popular and picked up by friends and colleagues in other disciplines and spread from there. The societies at which they were presented include the American Medical Association, the American Physical Society, and the American Psychological Association. For those skits with some math in them, the people in other disciplines simply replaced the math content with content appropriate to their fields as the subject matter was not the point of the skit.

In fact, the Wall Street Journal picked up two skits and created comic strips from them to illustrate points in a full page article on The Gender Gap, published on page B9, September 11, 1992. The one at the top of the page is about differential treatment in the classroom. I am pleased to report that I have not heard of that type of behavior happening since 2000. For the same article, the Wall Street Journal picked up another skit, one about a micro-inequity that still happens regularly to almost all professional women.

On the Telephone

MC: A female professor is seated at her desk in her office. The scene opens with her picking up a telephone and initiating a call.

Dr. Jones: Hello. This is Dr. Jones from Enormous State University calling for Dr. Smith.

Secretary: Please hold while I see if he is in.

Pause

Secretary: Dr. Smith is available. Please put Dr. Jones on the line.

Dr. Jones: This is Dr. Jones.

Secretary: Yes. Dr. Smith is ready to take the call. Please put him on the line.

Dr. Jones: Dr. Jones is on the line and I am a her not a him.

Secretary: Oh.

Pause

Secretary: I'll connect you now.

Dr. Smith: Hello, this is Dr. Smith.

Dr. Jones: Hello. This is Dr. Jones from Enormous State University.

Dr. Smith: Yes, please put him on.

Curtain

The exceptional women are those, like me, with unusually low-pitched voices. We get called "Sir," on the phone instead. This seems to be a no-win situation.

As noted above, our skits went beyond the math community to other organizations. Some of us used them as teaching tools at other meetings. Some men now recognized when they were acting inappropriately and shared examples with us. The broader participations in the discussions of micro-inequities meant that there was a there there (with apologies to Gertrude Stein). We all goof sometimes, and apologies go a long way to making a more congenial atmosphere.

Of course, our skits were not the only things going on to improve the climate for women in math, the broader STEM community, or non-STEM professions, but I think they helped. Mathematicians are usually good at generalizing. One personally lovely result came from a full-professor in my own department who not only came to a set of skits, but also stayed for the discussion, and ended the evening by telling me that he should have apologized to me years before for saying women should not be full-professors and that I added a lot to the department. Not all results were so positive. The person who did not see himself in his skit still does what was depicted in the skit and still commits the same micro-inequity. Several men have tried to explain to him how times have changed since the 1950s and why his behavior is no longer acceptable, but he cannot absorb the magnitude of his error in current culture.

The big changes I see, for whatever reason, are that not only are there more women in many departments but also they are treated better. Women are still often underpaid but not by as much as we used to be. Gone are the days when a female full professor made less than the newly hired male assistant professor. If a male professor puts a female student down, not only do male students complain, but male faculty support the female students. Departments and their deans seek more diversity than they once did; one female in a faculty of 30 or more is no longer seen as sufficient. Back in the 1980s, major math meetings often had no female speakers or at most one; now it is common to see several women giving plenary talks and organizing special sessions.

But we have not solved the inequity problem completely. Sometimes a bigger service burden is still put on the women. A recent occurrence at a major research university was that a woman running a departmental program repeatedly asked for staff help for some jobs she had been doing for years that had grown to be a burden. She was told that there was none available. Yet when she suggested that one of the male permanent associate professors who was not very productive could help, she was told that this type of work was for staff, not faculty. A friend reported to me in 2017 that her department has claimed that there weren't any qualified female applicants after hers, yet she looked at the files for the last few years and saw qualified female applicants. She is not the only one who has told me about such behavior recently, yet I have heard of other departments who are actively recruiting women, so better but not solved.

Naturally, as we solve some problems or eliminate some poor behaviors, new ones may arise to take their place. The one issue that bothers me most, and lots of other male and female tenure-track faculty too, is that many research (and non-research) schools now depend on non-tenure track faculty for teaching. To make matters worse, that category is becoming largely female. Two body problems are too often, but not always, solved by hiring the man on tenure-track and the woman as non-tenure track. The growing number of non-tenure track faculty is, to lots of us, a major problem in and of itself, but using female non-tenure faculty to make departmental percentages of female faculty look good has got to stop.

Another unsolved problem is the unconscious bias that work produced by males is inherently better than female-produced work. I suspect we've all heard about the mathematician who had a sex change from male to female and whose first NSF reviews afterwards came back that she was not as good as her brother. I continue to hear about the old discussion as to whether a female co-author did her share of the work with doubts expressed, even in 2017. Yet this bias is not as strong as it used to be in that women are having their papers accepted in better journals at a rate closer to the male acceptance rate than they did 30 years ago.

And so it goes—one type of inequity is gone or not as prevalent and another remains to be solved. But the skits in particular and humor in general do help promote peace between people or at least help people be aware that there is a problem to be addressed. As Rabbi Tarfon (c.47-c.117) is reported to say in the Pirkei Avot (The Sayings of Our Fathers), Avot 2.16 "It is not incumbent upon you to finish the task, but neither are you free to absolve yourself from it." We tried to do our part.

Chapter 19
Teaching Students About Women and Mathematics: An Interview with Two Course Designers

Jacqueline M. Dewar and Sarah J. Greenwald

Abstract Women in mathematics have made great strides during the last 100+ years. During this same period, educators, historians, and mathematicians have publicized the accomplishments of some of these women in order to provide role models to show that women can and do succeed in mathematics. As a part of this effort, faculty began offering entire courses on women and mathematics at the college level. In this chapter we describe our motivations for designing and teaching such courses. Using a series of interrelated questions formatted as an interview with two course designers, we highlight commonalities and differences in our approaches to teaching about women and mathematics. We also explore ways to teach about women and mathematics on a smaller scale, rather than as an entire course. For those who would like to adopt or adapt one of these approaches, we discuss benefits and challenges and provide references to our own and other courses on women and mathematics.

Keywords Course design • Mathematics education • Women mathematicians • Women's studies • Role models

19.1 Introduction

How can we help inspire and retain mathematics majors from diverse backgrounds? Role models for doing mathematics are cited as one important factor [1, 6, 17, 20, 25] and a desire to provide role models prompted each author to design and teach entire courses on women and mathematics. These courses can be designed in a variety of ways [2, 8, 9, 12, 14, 16, 21, 23]. The content level can range from including

J.M. Dewar (✉)
Loyola Marymount University, Los Angeles, CA, USA
e-mail: jdewar@lmu.edu

S.J. Greenwald
Department of Mathematics, Appalachian State University, Boone, NC, USA
e-mail: greenwaldsj@appstate.edu

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a great deal of mathematics, to critical studies of the available statistical research, to historical, sociological, and feminist perspectives. The interdisciplinary nature of these courses allows for offerings in mathematics, women's studies, education, and other departments. This chapter expands on a talk the authors gave at MathFest 2015 in the Association for Women in Mathematics (AWM)-Mathematical Association of America (MAA) Contributed Paper Session on "The Contributions of Women to Mathematics: 100 Years and Counting." In what follows, we use an interview format to pose and respond to a series of questions about many facets related to teaching students about women and mathematics.

19.2 Why Did You Design a Course on Women and Mathematics?

Jackie Dewar: I first offered my course on women and mathematics in 1979, but the rationale for doing so goes back nearly a decade before that. I was in graduate school before I heard that a woman had made significant contributions to mathematics. In a graduate course on ring and field theory I learned about Noetherian Rings and Emmy Noether. I did not think young women (or men) should have to wait that long to learn that women had made important contributions to mathematics, nor should they need to have gained admission to a graduate mathematics program. Teri Perl's 1978 book, *Math Equals* [19], informed me that at least nine women, including Noether, had achieved some degree of recognition for doing mathematics from the fourth to the twentieth centuries. *Math Equals* inspired me to design a course about women and mathematics. But it did more than that: it provided me with a model for combining the biographies of women mathematicians throughout history with mathematical activities related to their work and including a discussion of the situation for women mathematicians in modern times. (For more information about Teri Perl, see Chapter 8 in this volume.)

Sarah Greenwald: A woman mathematician inspired me too. Specifically, it was a quote by Julia Robinson:

> What I really am is a mathematician. Rather than being remembered as the first woman this or that, I would prefer to be remembered as a mathematician should, simply for the theorems I have proved and the problems I have solved [7, pp. 271–272].

At the same time, I was concerned that my students were unable to name one woman or minority mathematician. That was true even of those who would eventually self-select into my course. Because role models had been so fundamental in my own decision to pursue mathematics, I wanted to find ways to provide them for my students. I was a first-year faculty member when I began developing the course. I created a senior seminar on women and minorities in mathematics that includes significant mathematical content. We explore the work of mathematicians along with history and equity issues in a way that I believe would have satisfied Julia Robinson.

19.3 What Audience Did You Have in Mind When You Designed Your Course?

Jackie: In my case, the first audience (spring of 1979) was anyone who needed a mathematics credit to graduate, but whose major did not include any mathematics courses, so the course satisfied a mathematics core requirement. I circulated a flyer with a brief course description written in a way to allay the fears of potential students about mathematics. As a result, the course attracted many self-described “math-phobics.” I taught the course once every few years, whenever it could fit into my teaching schedule.

Twenty years later, a special quantitative literacy (QL) course was developed to satisfy the university’s mathematics core requirement. Although a student could petition to have the women and mathematics course count for her (or his) core requirement, the advent of the QL course essentially eliminated this audience. At that point I realized that future K–12 mathematics teachers would be the perfect audience for the course, because whatever they took away from the course had the potential to reach so many students in the future. So, I redesigned the course with that population in mind, but mathematics majors with no plans to teach also take the course.

Sarah: With appropriate modifications, these kinds of courses can benefit almost any student and a single course can even serve multiple audiences at the same time. Discussions with a faculty mentor in the chemistry department about our shared interests in women in science and mathematics led me to apply for funding from the Women’s Studies program, now called Gender, Women’s, and Sexuality studies (GWS), to design and teach such a course. My interdisciplinary seminar would be aimed at seniors and cross-listed as a mathematics course and a GWS course. The idea was that the mathematics students would focus on the mathematics while the GWS students would focus on feminist and equity perspectives. Presentations and class discussions would be general enough for everyone to at least somewhat follow along and the entire class would benefit from the diversity of interdisciplinary perspectives. A few students who were majoring in mathematics or physics and also interested in women’s studies took the course. However, it was more beneficial for them to register for the mathematics credit. In the two runs of the course, no GWS students who were not already involved in STEM ever enrolled, so I never tested the underlying model.

I have modified portions of the course for use in other settings, such as in a mathematics course for liberal arts students and in a first-year seminar on breakthroughs and controversies in mathematics. A great variety of majors, including those from humanities, social sciences, and education, enroll in these courses. This material is just as beneficial for them as for the STEM students who enroll.

Jackie: My course has been cross-listed too—originally, with women’s studies and later on as an honors course. Speaking of enrollments, the original version of the course typically enrolled 25 students. After being redesigned with future teachers in mind, the enrollment varied from six or eight up to a dozen. Once, when the Director of the Women's Studies program enrolled a whole cohort of her students in the cross-listed version of the course, the total enrollment went up to 23. In that case, time constraints meant that students worked together in pairs on their biographical poster presentations.

Sarah: Seven students enrolled the first time I offered the women in mathematics seminar course as a senior-level elective. When I broadened the focus to include both women and minorities in mathematics, 18 students enrolled. I have adapted the projects from the course to use as a small part of freshmen-level courses with 25 to 35 students and junior and senior-level courses containing 10 to 20 students. I encourage but do not require group work. I do require that each member of a group speaks during presentations.

19.4 What Are the Goals (or Learning Outcomes) for Such a Course?

Jackie: My original course predated the practice of delineating specific learning goals and outcomes, so I will only describe the goals and outcomes for the redesigned version. Basically, I want the students to learn about the lives and work of women mathematicians past and present, understand current gender issues in mathematics participation and careers, and engage in doing and communicating mathematics in a supportive environment. Here are the four general course goals, each with more specific learning outcomes, and a fifth goal and learning outcome for students who identify themselves as future teachers.

1. To examine the lives and contributions of women mathematicians from the 4th to the 21st centuries

   Learning outcomes: Students will be able to

   - Describe the life and work of nine women mathematicians and at least one contemporary woman mathematician
   - Synthesize from these women's biographies common experiences and obstacles faced by women who wished to participate in mathematics and identify factors that enabled their success.

2. To investigate current gender issues related to women's skills and participation in mathematics from elementary school through graduate school and their participation in mathematics-related careers

   Learning outcomes: Students will be able to

   - Discuss the current situation in the United States regarding women's participation and achievement in mathematics in K–12, higher education, and industry
   - Read critically articles in journals and newspapers dealing with gender issues in mathematics or science education.

3. To provide students an opportunity to experience "doing mathematics" in a supportive and cooperative environment and to encourage students to be more aware of their own mathematical thinking

   Learning outcomes: Students will be able to

   - Make and investigate mathematical conjectures, develop arguments in support of or counterexamples for those conjectures
   - Communicate their mathematical thinking clearly to others (peers and instructors) using mathematical language
   - Analyze and evaluate the mathematical thinking of others
   - Recognize and give examples of: mathematics as a study of patterns; the critical and distinct roles of inductive and deductive reasoning in exploring mathematics; the existence and utility of multiple representations for many mathematical concepts.

4. To undertake a scholarly investigation that explores one or more of the above areas

   Learning outcome: Students will be able to

   - Demonstrate the ability to conduct an interdisciplinary research project.

5. (For future teachers) To develop expertise in addressing equity issues related to mathematics education at the level you plan to teach

   Learning outcome: Future teachers will be able to

   - Prepare and share mathematics teaching resources and lesson plans (including appropriate assessments) that reflect equity principles.

Sarah: A primary goal in the senior seminar was to learn how to research, evaluate, and summarize information, including mathematics, history, and gender and racial issues. Students would explore mathematical content by reading research articles by women and minority mathematicians. With my help, the students learned to focus on an aspect of the mathematics. If the student had no experience with the topic, they could connect a short summary of the mathematician's research article to a general introduction to the field through definitions, examples, and history. Students who had the mathematical background explored the theorems. In all cases, whether it was a short summary or a more extensive investigation of the article itself, the mathematician's work was the primary motivation for pursuing the related mathematics. Students also researched the mathematician's life and work as well as aspects related to gender or race. I hoped this would provide role models to help retain majors from diverse backgrounds. In the process the students learned how to find information in various sources including books, the Internet, MathSciNet, the library, and reference lists, and they developed the ability to summarize and critically evaluate sources. Had any GWS students registered, I would have flipped the emphasis: their research would have only briefly touched on the mathematics while the majority of it would have been related to the gender aspects in society at the time and in the mathematician's experiences.

Another major goal of the course was to learn how to communicate effectively. The students wrote papers and engaged the rest of the class through presentations and classroom worksheets they created on the mathematicians whose research papers they read. The papers mainly focused on the mathematics but they also included a brief summary of the mathematician's life and work as well as issues related to gender, race, or multiculturalism. Many of the students were pre-service teachers, so we explored how to incorporate the mathematics into their future classrooms when the students presented to each other, created the worksheets, and completed mathematical activities in each other's worksheets. Additional information about the creation of the worksheets and a sample can be found in [9]. I asked them to aim their presentations and worksheets at the level of our class, so they could assume common requirements for the major, which included calculus and linear algebra. The paper was typically aimed at a higher level. In the final project, they communicated their work in a webpage format.

While most of the course objectives related to information literacy and communication goals, there were a few additional goals I should highlight. Overall, the students were to explore many topics in pure and applied mathematics research and numerous gender and racial issues. As a survey course we could explore the breadth of mathematics and real-life experiences of women and minorities in mathematics. I also wanted students to see the historical progression of mathematics, including the mathematics of living mathematicians, and to connect mathematics and society.

19.5 What Is the Content and Structure of the Course?

Jackie: Interdisciplinary courses like these can include any topics from history, mathematics, social science, social justice, or education that can be connected to women and mathematics. The mathematical topics in my course relate in some way to the work of the women whose biographies we study, and they range widely: conic sections, prime numbers, limits, the cycloid curve, infinite series, congruence arithmetic, difference equations, Euler's polyhedral formula, symmetry groups, and much more.

To connect these disparate mathematical topics, the course emphasizes three recurring mathematical themes:

- Mathematics, at its core, is the study of patterns;
- Inductive and deductive reasoning play distinct, important, and complementary roles in mathematics;
- Multiple representations not only exist for a single mathematical concept, but they can be incredibly useful.

The focus on patterns also provides a powerful approach to the biographical material. We explore what patterns the women's lives exhibit and how they change over time.

The material on gender equity examines questions such as: What sort of gender differences exist in mathematics ability, performance, and participation? How have these changed over time? Why are so few women mathematicians known to students today? What are possible explanations for why women do not participate in mathematics-related careers to the extent that men do? Why should this underrepresentation of women in mathematics-related fields be a matter of concern? What might remedy this situation? We also explore topics such as stereotype threat, the perception that the best mathematics is done when young, whether mathematics is more of an individual or a community pursuit, and how these ideas might affect women's participation in mathematics (see [13]).

Students take bi-weekly quizzes containing questions on both the mathematical and biographical material. Each week, on an electronic discussion board, students post answers to questions posed about the biographies and other readings. We continue the discussion begun there in class. Their first major assignment is to write a short paper synthesizing the initial readings on gender equity. Later each student selects a topic for a longer paper on women and mathematics or mathematics teaching. The work on this paper is divided into stages, and at the midway point each student gives a two-minute "elevator speech" to the class about their topic. The final product is a formal research paper submitted in writing to the instructor. Near the end of the semester students make an electronic poster and give an in-class report on a modern woman mathematician. In this report students describe the life and work of the woman and then compare and contrast her educational opportunities, family responsibilities, and career experiences with those of the women from the past. Instead of a poster, a future teacher may opt to develop a lesson plan that connects to a woman mathematician. At the end of the semester, students complete a final portfolio that encourages them to reflect on and respond to the course goals. For example, here is one of the prompts in the portfolio assignment:

> Draw on material from this course to craft a response to this hypothetical blog posting. On the "MenRSmartR" blog you read: "In all of history there have been no women geniuses. This clearly indicates males have a superior intelligence!"

Sarah: My senior seminar was organized around four projects that primarily explored mathematics, but also included life and work summaries of individual mathematicians, as well as gender, racial, or multicultural aspects of their lives. For the first project, students chose a mathematician from the 18th and 19th centuries. In order to provide the students with contextual information, we discussed the early history of the education of women and African Americans in the United States. Then I presented Hypatia of Alexandria's life and possible editorial work to provide the students with a model for their research and presentations. Fictional tales and a fictional picture of Hypatia have propagated through the literature as fact during the last 100+ years and we discussed this as a cautionary tale to include diverse and up-to-date sources. We also discussed the work of historians like Wilbur Knorr and how he hypothesized what Hypatia may have worked on [15]. For the first project I provided them with the material they would need to begin to explore the mathematician's life and work and aspects related to gender, race, or multiculturalism. I printed any materials that were not available online and lent them to each student in a folder. After presenting the first project to the class they began working on the second project, which focused on mathematicians born between 1900 and 1925. By this point in the class, students' research skills had developed sufficiently that they could be more independent. However, I gave them a list of mathematicians to choose from so that I could continue to help and monitor their progress. The list included mathematicians with local connections such as Beauregard Stubblefield, who had spent some time at my university, and Marjorie Lee Browne, who had worked at North Carolina Central University, which is also close to the university and to many students' hometowns.

In between project presentations we examined a variety of topics, such as research on mentors and role models, ability to perform mental rotation tasks, and testing issues, such as stereotype threat. Periodic online quizzes helped the students solidify their knowledge and make additional connections. For the third project, students were free to select any mathematician born after 1925. For their final project, which was web-based, students chose a mathematician they had investigated in the first three projects to revisit in the context of what we had learned. I asked them to add to their original project by comparing their mathematician's experiences in school with what other women or minorities experienced in school during that time, and to place gender, racial, or multicultural issues in the context of a theme studied in class, such as noting how strong support systems help to overcome discrimination. They also created webpages derived from the classroom worksheet they had previously constructed on their mathematician. They added an introduction to the worksheet that included the objectives and the mathematical background needed for the worksheet. They researched and created a mathematical genealogy for the mathematician and provided an annotated bibliography. While they could work in groups on the first three projects and turn in one project per group, they worked individually on the final project, each student researching a different mathematician.

19.6 What Are Some of the Challenges in Teaching Such a Course?

Jackie: My biggest challenge for the latest version of the course has been to provide mathematical experiences that are accessible and valuable for both future elementary and secondary teachers, who bring a wide variety of mathematical backgrounds to the course. The mathematical activities have to be designed with multiple entry points and optional trajectories, making them accessible, novel, and appropriately challenging for all of the students.

Sarah: I agree that accommodating a wide variety of backgrounds and interests takes some careful thought and planning. Another challenge common to any course focusing on historical perspectives is outdated or unreliable sources. For instance, in the case of Evelyn Boyd Granville, numerous sources list her as the first black woman to obtain a PhD in mathematics, because that was the current knowledge at the time of those publications. That perspective proliferated through the web and literature until Euphemia Lofton Haynes' earlier PhD was publicized by Scott Williams through his Mathematicians of the African Diaspora website (http://www.math.buffalo.edu/mad/). After presenting this information as a caution to the students, I asked them to search for a variety of sources, including recent sources, and to look for inconsistencies and respond to them.

In general, there is an abundance of information available, and while that is mostly a positive, it can be overwhelming for a teacher designing a course or a student researching a project. The information also changes rapidly. New studies, interviews, and articles appeared in the literature and in the media each time I taught the course. I brought these into the classroom to show students the changing nature of the fields as well as the relevancy.

Other changes occurred at my university, such as new general education requirements, something Jackie also encountered. As I began to teach newly required first-year seminar and senior capstone courses, I no longer had time in my schedule to teach the senior seminar on women and minorities. As a result, the original course has morphed into other, smaller-scale, implementations, which are detailed in Section 19.8.

Jackie: I definitely agree with Sarah that keeping material up-to-date is indeed another challenge of teaching a course like this, and I want to point out that this might not occur to someone used to teaching undergraduate mathematics courses. I am always on the look-out for new project topics to suggest to students, revising and updating references for the ones I already have on the list, and deleting ones that seem dated.

From the very beginning, my course has been cross-listed between mathematics and women's studies, but initially to get such a cross-listing was a challenge. Women's Studies resided in the College of Liberal Arts, while Mathematics was in the College of Science and Engineering. So two deans were involved. I was told by the then Dean of Liberal Arts that if there was enough mathematics in it to be a mathematics course, he couldn't see how there could be enough about women to be a women's studies course, and vice versa. In the end, he went along with the Associate Dean of Science and Engineering who was only too glad to have another option for students needing a general education mathematics course.

Sarah: That's very interesting, Jackie. I feel very lucky that the departments I worked with were so supportive and flexible at the time, but I do have to admit that I was always quite aware of the need to advocate for my course, especially when I was speaking to mathematicians about it, both at my school and beyond. I was always very careful to highlight the mathematical breadth and depth that would be an integral part of the senior seminar. It is also fairly easy to find recommendations from professional societies that can help justify such courses. For example, the Mathematical Association of America specifies that "Programs should introduce historical and contemporary topics and applications, highlighting the vitality and importance of modern mathematics, and the contributions of diverse cultures" [22].

Jackie: Fortunately, everyone at my institution has been very supportive once the course got underway. And I now have evidence to show that by emphasizing those mathematical themes I mentioned, it is possible to shift students' views of mathematics away from the idea that it is just about numbers and toward seeing it as a study of patterns that involves structure, abstraction, and generalization [3].

Sarah: Another issue that instructors may want to consider relates to role models. Anytime I bring up a mathematician in one of my classes, I think about the mad scientist and genius stereotypes that are so prevalent in students' prior conceptions of who succeeds in mathematics and I work hard to balance those stereotypes with more approachable role models [10].

19.7 What Are Some of the Rewards?

Jackie: One of the first things to come to mind is the positive feedback I have gotten from former students, especially years later. About ten years ago, a Loyola Marymount University staff member, who had taken the original version of my course, told me how it was the best mathematics course she had ever had. More recently, about five years ago, I observed the classrooms of four of my former students who are now teaching and I conducted semi-structured interviews with them about their teaching, their concerns about equity, and my course. The results of this study are reported in [5]. It was incredibly rewarding to actually see, hear, and document how their concerns for equity expressed as future teachers in my course are now playing out in their classrooms, and how some of them are using lessons or materials from the course.

Sarah: Like Jackie, I have found that one of the benefits is the great feedback from students, both current and former. One of my former students, Danny Eldreth, was teaching middle school in a neighboring county when he invited me to speak to his eighth grade honors mathematics class. I discussed my life and work with the students as they asked me questions. They also gave me a summary of what they had learned from a lesson on mathematicians that Danny had adapted from his experiences in my class. It was just as inspiring, if not even more so, to hear the students talk about the impact of what they had learned, as it had been to hear about the impact it had on Danny. That is one of the joys of working with students who plan to teach—the possibility for broad reach.

Interesting discussions and presentations permeated my courses and these filled me with hope for the future. It is uplifting to hear students discuss mathematics, mathematicians, and social justice issues in the context of the senior seminar.

I was pleased with the amount of effort students put into the class. One student remarked that the projects were "kind of hard sometimes, but very good." Another student commented that she felt that this class helped her in advancing her ability to do research and speak about mathematics, and that the class was very encouraging. I also enjoyed seeing the progression of the students' awareness. At the start of the senior seminar they knew nothing, or next to nothing, about mathematicians, and by the end of the course they were seeing themselves as a part of the mathematics community. I asked them who they identified with the most, and why. For some students it was the way a mathematician discussed their learning or research style, which felt familiar. For others it was the stories or quotes that helped connect them to a mathematician. Their responses varied considerably. One student, who became a high school teacher, noted that this was one of the few classes in the department from which he could walk away and actually say, "I will use this in my classroom."

Jackie: Sarah, you are right. This is definitely one of those courses where the instructor can really see student growth from beginning to end. I wonder whether you will agree that what I am about to mention is a reward, as some might see it as a challenge. Potential instructors may feel their background in history or gender studies is insufficient to teach a course like this, but that can mean it presents an opportunity to learn many new things, as well as how research is conducted in other fields. I can still remember my amazement at learning how inventory records of an estate sale at her father's death in 1752 revealed that Maria Agnesi's "working library was four hundred titles strong" [18, p. 93] and what those titles could tell us about her education and the resources available to her while she worked on her book *Analytical Institutions*. So the reward of learning new things is there.

Sarah: It is a great opportunity to create a shared learning environment where I am not always the expert. Some of my students knew more than I did about the women's studies topics. Others had taken statistics or mathematics classes that related to course content and which I had not. When they chose such a topic, grading became very interesting. The positive environment more than made up for any difficulties. From the beginning I explained that a seminar class is where the seeds of research are planted. Not only did I enjoy learning from my students, but they also became more independent and critical thinkers, rather than looking to me for answers.

Jackie: Another reward is when professional colleagues and others are interested in hearing about this course. I have spoken about the course at teachers' conferences and at a WiMSoCal (Women in Mathematics in Southern California) symposium, and used material from the course to give talks on campus during women's history month. The course recently afforded me the opportunity to speak at an international conference celebrating the 25th anniversary of the MacTutor History of Mathematics website, network with scholars who are currently researching the lives of Sonia Kovalevskaya and Ada Lovelace, and publish a paper [4].

An additional bonus for me was the opportunity to team-teach the course three times with junior colleagues: Lily Khadjavi (2008), Alissa Crans (2010), and Anna Bargagliotti (2012). This was made possible by funding from the MAA's Tensor Women and Mathematics program (http://www.maa.org/programs/maa-grants/women-and-mathematics-grants).

Sarah: I also found that it has been great to interact with other educators. In my case that happened as I was developing the class, in discussions with various people around campus, and afterwards in the form of workshops, panels, or talks at conferences. For instance, I spoke to teachers at North Carolina A&T State University's Sonia Kovalevsky High School Mathematics Day and Terri Bennett and I co-organized an AWM panel at the 2006 Joint Mathematics Meetings on "Teaching a Course on Women and/or Minorities in Mathematics."

19.8 What Are Ways to Teach About Women and Mathematics on a Smaller Scale, Rather than as an Entire Course?

Jackie: I recruit and mentor college students—even ones who have not taken the course—to lead a hands-on workshop for the junior high girls who attend a local Expanding Your Horizons career day (http://www.expandingyourhorizonsla.org/). We combine an activity that relates to the mathematics done by a woman mathematician—for example, Sonia Kovalevskaya—with the story of her life and the challenges she faced and successfully overcame to learn and then do some mathematics. For Kovalevskaya, students try to find and describe patterns in sequences. The activity includes a paper-cutting task to make a snowflake pattern that we investigate. We have also done a workshop based on Emmy Noether's life and work where the activity involved kinesthetic activities that were then recorded on worksheets. The results lead to the discovery of elementary properties of a group. The source for these activities is an instructor's manual written for teachers of grades three through eight [24]. It contains 23 units, each with a biography of a woman scientist, engineer, or mathematician, a description of her accomplishments, and directions and materials for a student activity related to the woman's work. Both the undergraduates and the younger students benefit. And many times the undergraduates continue leading the workshop for several years, even after they graduate.

Sarah: As general education requirements changed, I created an abbreviated version of the course to use as a small segment in other environments. I began with a segment for use in a mathematics for liberal arts class. The idea is that students choose from a list of mathematicians and present information about the mathematician's life and work to the rest of the class, along with a classroom worksheet they create. At the first-year level, I provide all the references they may need. I choose the mathematicians and references carefully, at the appropriate level, and to tie into course goals. These projects showcase diversity in the people, mathematics, and mathematical styles. Various versions of this segment have also made their way into a first-year seminar on breakthroughs and controversies in science and mathematics and a senior capstone for mathematics majors. Depending on the time constraints, student presentations within a shorter segment could take a day of class, a couple of weeks, or anywhere in between. In one formulation, at our AWM Student Chapter meetings, a student researches and presents some interesting information about a woman mathematician. I encourage them to bring in a photo, artifact, or other visual aid as well as information about their life and work.

I have also shared abbreviated versions of these projects as a small part of a Women in Mathematics Badge for Girl Scouts, which Amber Mellon, Jill Thomley, and I developed [11]. Before the participants come together for a day to complete the badge requirements, we ask the middle grades students to research Sonia Kovalevsky, along with AWM Sonia Kovalevsky High School and Middle School Mathematics Days (SK Days), and to find a meaningful quote by her. To make a connection with SK Days we use the "Kovalevsky" spelling of her name, although we do tell them that because her name is Russian, there are many different spellings of it. When we meet we discuss what the girls found as we talk to them about her life and work. We highlight some of Kovalevskaya's notable firsts and stories such as the mathematical wallpaper on her childhood bedroom walls. The girls are especially interested in the quotes, and they share their favorites with each other. During an interactive mathematical activity we engage them with some mathematics and quotes by other women such as statistician F. N. David and mathematician Evelyn Boyd Granville.

19.9 What Resources Are Available?

Jackie: More information about my course and a bibliography of resources are available at http://myweb.lmu.edu/jdewar/wam. This website has a downloadable manual with information and materials for teaching a college-level course on women and mathematics that addresses both the lives and work of women mathematicians past and current, and examines gender-related concerns about women's participation in studying mathematics and in mathematics-related careers. It also documents the outcomes of the MAA-Tensor grant (2007–2013), *Women and Mathematics for Future Teachers*, which funded the team-teaching of this course.

Sarah: More information about the courses and the programs I developed can be found at http://cs.appstate.edu/~sjg/awm/wam.html. This website contains day-to-day activities and homework, project assignments, references for students, and the mathematics discussed after each student presentation. Additional resources include articles on incorporating the mathematical achievements of women and minority mathematicians into a variety of college and high school classes and an article on role models. The Girl Scout badge steps and the program for completing them at a one-day event are also available and we are happy for others to use these materials.

19.10 Concluding Thoughts

We have tried to provide the readers of this chapter with information, resources, and encouragement to teach students about women and mathematics. We described what prompted us to begin doing so, the various ways that we have gone about it, and the rewards and challenges that we encountered. We teach at two very different institutions as one is private and has approximately half the number of students as the other, which is public. We also represent different geographical regions, one of us is on the west coast and the other is in the southeastern US. However, in writing our stories together we discovered quite a few overlaps and shared experiences. Our formal courses and other informal activities introduced our students to women mathematicians and engaged the students in doing and communicating mathematics. Both of us encountered changes in university curricula that affected how we taught these interdisciplinary courses. We also had to confront the challenge of giving students with widely varying mathematical backgrounds access to meaningful mathematical experiences. We wrestled with keeping our non-mathematical course material up-to-date. We both came to realize the great potential that working with pre-service teachers has to multiply—over many years in the future—the impact of the message that women can do and have done mathematics. We are in complete agreement that rewards abound for those who undertake to educate students about women doing mathematics. We will be very pleased if this chapter encourages some of its readers to find their own ways to provide role models for more of their students.

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Sarah: I would like to thank Appalachian State University for supporting a variety of my activities. The quotes from students first appeared in [8].

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Chapter 20
An EDGE in Mathematics for Women: The Enhancing Diversity in Graduate Education Program

Sylvia T. Bozeman, Susan D'Agostino, and Rhonda J. Hughes

Abstract The EDGE Program (Enhancing Diversity in Graduate Education) was initiated in 1998 by two mathematics professors from women's colleges, with the goal of helping women persist in graduate programs in the mathematical sciences. The program initially focused on the transition to and preparation for the first year of graduate school, with a commitment to diversity among participants, faculty, and staff. A four-week summer session featured courses that bridge undergraduate and graduate work, study groups, graduate student mentors, and professional and academic visitors, as well as social and team-building activities. Gradually EDGE expanded to support women throughout their graduate school and professional careers. What began with two founders and eight EDGE participants has grown to a diverse community of alumnae, more than 48% of whom are from groups underrepresented in the mathematical sciences. This article chronicles the impact of the EDGE Program on participants and the emergence of a new generation of leaders in the mathematics community. Lessons learned that may benefit others involved in related efforts are shared.

Keywords EDGE program • Mentoring women • Underrepresented mathematicians • Women mathematicians • Graduate students

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Sylvia Bozeman and Rhonda Hughes are the EDGE Co-Founders. Susan D'Agostino is the first EDGE participant to have earned the Ph.D. in mathematics.

S.T. Bozeman (✉)
Spelman College, Atlanta, GA, USA
e-mail: sylvia.bozeman12@att.net

S. D'Agostino
Southern New Hampshire University, Manchester, NH, USA
e-mail: s.dagostino@snhu.edu

R.J. Hughes
Bryn Mawr College, Bryn Mawr, PA, USA
e-mail: rhughes@brynmawr.edu

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20.1 The Founding of the EDGE Program

> No one is born smart. No one is born knowing how to read, right? No one is born knowing how to do math, or no one is born knowing how to play the flute—all of that comes with a lot of hard work…The only way you know how to read is that you keep trying."—First Lady Michelle Obama at Savoy Elementary School on May 24th, 2013.

Chaos theory offers a conceptual framework for understanding how the EDGE Program increased the participation of women, including those from underrepresented groups, in the American mathematics community. A principal feature of chaos theory is the so-called "butterfly effect," whereby a small, seemingly remote disturbance can have a significant impact on events. In the case of the EDGE program, the "butterfly" was mild-mannered American civil rights activist and mathematician Lee Lorch. At the Joint Mathematics Meetings in Atlanta in 1990, he introduced Rhonda Hughes of Bryn Mawr College and Sylvia Bozeman of Spelman College with the simple utterance, "You two should know one another. You care about the same issues." The two women's college mathematics department chairs took his words seriously; that quiet introduction spurred a series of events that resulted in a powerful metaphorical and literal disturbance within the mathematical community known as the EDGE Program.

Initially, Hughes and Bozeman established the Bryn Mawr-Spelman Summer Mathematics Program[1] in order to provide research experiences in mathematics for first- and second-year women college students. The program, which ran for four summers, sent a noteworthy 60 percent of its participants to graduate programs in the mathematical sciences. However, after receiving feedback from their own alumnae and noting the number of well-prepared women who left graduate programs in mathematics for both academic and non-academic reasons, Hughes and Bozeman determined that there was an even greater need to support women graduate students. These concerns about graduate student attrition had already garnered some national attention. In 1992, the National Research Council conducted a study, "Educating Mathematical Scientists: Doctoral Study and the Postdoctoral Experience in the United States." One goal of the study was to determine what factors make certain doctoral programs in the mathematical sciences successful in producing large numbers of domestic Ph.Ds., including women and underrepresented minorities. The committee conducting the study observed in its site visits that departments that promote the success of women and underrepresented minorities often find that those students do indeed succeed. Nevertheless, there was still no perceptible national effort to address both academic and non-academic issues leading to high attrition rates, especially among seemingly well-prepared women in mathematics.

Driven by a steadfast commitment to a more diverse mathematics community, Hughes and Bozeman co-founded the EDGE Program to provide broad transitional support for women, particularly women from underrepresented groups, entering

[1]This program was also called the Spelman-Bryn Mawr Summer Mathematics Program for two years.

mathematics doctoral programs. They received the support of students, faculty, and administrators at their home institutions, as well as from the National Science Foundation (NSF). Lloyd Douglas, an NSF Program Officer who strongly believed in the viability of the EDGE idea, searched relentlessly to secure partial funding for the initial year. In addition to the NSF, the program was supported by the Andrew W. Mellon Foundation, the National Security Agency, and the many institutions that hosted the program. For the first four years, EDGE alternated between Bryn Mawr and Spelman Colleges. Subsequently, ten colleges and universities across the US (listed later) hosted the program.

The following quote, widely attributed to anthropologist Margaret Mead, aptly describes the national community that banded together to support the EDGE program: “Never doubt that a small group of thoughtful, committed citizens can change the world; indeed it is the only thing that ever has.” In this case, the world that has been changed is that of American mathematics. At the start of the 21st century, the American Mathematical Society (AMS) designated EDGE as a “Mathematics Program That Makes a Difference,” noting its “success in improving the diversity of the profession of mathematics in the United States” [8]. The EDGE Program has had a positive, significant impact on the number and diversity of American women earning mathematics doctoral degrees and serving as leaders in the scientific community, as demonstrated in the following sections. Nonetheless, as the EDGE Program joins other entities addressing an entrenched problem in the United States, the need for continued intervention remains strong.

20.2 The EDGE Program Philosophy and Goals

The EDGE philosophy is that students who delight in the study of mathematics, perform exceptionally well at the undergraduate level, and have been identified as possessing abundant potential by their undergraduate mathematics professors are capable of success at the graduate level. This philosophy is a response to a frequent and unfortunate phenomenon witnessed by Bryn Mawr and Spelman faculty, as well as faculty at colleges and universities around the country: well-prepared, academically talented, undergraduate women are accepted into mathematics graduate programs, only to leave those programs without the intended degree. The resultant mathematics graduate program attrition represents a substantial loss of talent in and negatively impacts the gender and racial diversity of the mathematics community. Graduate school is often a high-performing student’s first encounter with perceived failure. A young woman who performs below her own high expectations may conclude that she does not have what it takes to succeed. On the other hand, if she is provided with an understanding of the culture of graduate school, a standard of measurement by which to judge her performance, a guide for realistic expectation, and a community within the department to trust for advice, evidence suggests that she can and often does succeed. Further, women who come from small undergraduate mathematics departments with few advanced mathematics elective options often believe that they were not exposed to enough mathematics necessary to succeed.

The EDGE philosophy affirms that a student who excelled in her undergraduate mathematics department is capable of earning a doctoral degree in the mathematical sciences. In support of this philosophy, the EDGE program established two primary goals:

- Provide academic enrichment, cultural exposure, and mentoring to bridge the transition from undergraduate to graduate mathematics programs for women from diverse backgrounds.
- Diversify the mathematics community in the United States.

As EDGE evolved, the directors established the following secondary goals in response to needs of program participants:

- Mentor women during and after graduate school in order to provide timely support, and to produce leaders in the scientific community.
- Establish a community of participants, alumnae, faculty, and staff that provides support, tiered mentoring, and networking opportunities.

Driven by the passion and extraordinary potential of EDGE participants, faculty, staff, directors, and supporters, EDGE has evolved into a dynamic national organization. While holding true to its original mission of supporting diversity in mathematics graduate education, EDGE has cultivated a built-in agility that responds to emergent participant needs.

20.3 Components of the EDGE Program

One of the greatest challenges for new mathematics graduate students is navigating the transition from undergraduate to graduate mathematics departments. During this academic and cultural transition, students must forge relationships in a new culture, learn unwritten rules, and maintain their own identities and values. As such, the central component of the EDGE program is a four-week summer session designed to:

- Provide bridge courses in algebra and analysis that connect undergraduate and graduate mathematics.
- Provide engaging activities that introduce entering students to the culture, rigor, pace, study expectations, and challenges of graduate mathematics as well as to mathematicians with whom they can relate.

The summer session bridge courses/workshops and activities are led by a diverse staff of primarily women mathematicians and advanced graduate students. They assist participants in learning to work, speak, and socialize across academic, cultural, social, and other boundaries. For example, the "Difficult Dialogues" seminar is designed to foster an appreciation for individual talents and uniqueness.

Through guided activities, participants build self-confidence in negotiating new environments with people from diverse backgrounds. The summer session also provides participants with opportunities to hear graduate students and faculty discuss their experiences and offer advice on navigating academic, social, and political encounters in mathematics doctoral programs. The preview of graduate school that the EDGE summer session provides offers an "edge" that prepares students for the year ahead and supports their abilities.

The EDGE Program has evolved to include additional components that provide continuous contact, support, and mentoring to participants beyond the summer session. The EDGE Reunion Conference is a weekend during which the previous year's participants, having completed their first year of graduate school, return to the EDGE summer session. These students reconnect with EDGE directors, faculty, and graduate student mentors for debriefing and advice. They meet and speak with recent EDGE Ph.D. recipients, share stories of challenges they had to overcome with current EDGE participants, and attend research talks. Students also share their experiences in their own words with a special sensitivity to the audience. For example, one EDGE alumna explained to current EDGE students that learning to handle graduate mathematics courses was "a lot like learning to walk in high heels on a rocky path." The Reunion Conference provides current and past participants with palpable evidence of EDGE's warmth, support, and singleness-of-purpose.

The EDGE program also supports additional activities designed to strengthen community, encourage professional growth, celebrate diversity, and showcase the work of current and past participants at national and international venues. Activities have included:

- *An annual EDGE reunion held at the annual Joint Mathematics Meetings (JMM).* Although this annual gathering is less intensive than the summer session reunion, it continues to establish mid-academic-year contact and fosters networking among EDGE community members at all academic and professional stages.
- *Several EDGE-specific JMM Special Sessions.* The sessions titled, "Pure and Applied Talks by Women Mathematics Warriors," have been regularly organized by past EDGE participants and graduate student mentors at the 2014, 2015, 2016, and 2017 JMM.
- *An EDGE-specific AWM Research Symposium Special Session (in 2015 and 2017).* The organization and leadership for the sessions have been provided by EDGE participants and mentors.
- *An EDGE-specific mini-symposium at the 7th International Congress on Industrial and Applied Mathematics (July 2011, Vancouver).* The mini-symposium, titled "Applications from the EDGE," was co-organized by an EDGE faculty member and a past participant. The four symposium speakers were all past EDGE participants, including three from underrepresented groups.
- *Small research funding opportunities for current and past participants.* Since the beginning of the EDGE Program, students have been allocated a small research fund to be used during their first graduate school year following the initial four-week summer session. In later years funding was made available to support

research travel by advanced graduate students and recent PhDs. Many first-year students apply the funds to books while advanced graduate students typically use the funds to offset costs of traveling to attend or present at scientific conferences.
- *EDGE newsletters*. Two newsletters, which were produced and distributed by past EDGE participants in 2010 and 2012, provided a venue for reporting on personal and professional accomplishments and for maintaining connectivity. Later the community turned to other media platforms to achieve some of these goals.
- *EDGE-specific social media platforms and a listserv*. These mechanisms support communication among EDGE community members. The directors hope to identify a method for evaluating the impact of these technologies.
- *Research Mini-Sabbaticals*. Funding is provided, by request, to past participants who are advanced graduate students, recent PhDs or junior faculty to advance the work and intellectual growth of recipients as well as increase their visibility within the mathematics community. A Research Mini-Sabbatical may provide funding to spend two to six weeks working with a collaborator.

As the number of EDGE participants grew, it became a significant challenge to support and mentor every past participant until she earned the doctoral degree. Attempts to address this challenge led to the formation of regional Mentoring Clusters. Although peer mentoring seemed to occur organically, a formal structure was needed to increase personal contact with senior faculty. In order to meet this challenge the co-directors established Mentoring Clusters in geographical regions where there was a significant number of EDGE students in graduate programs. Each cluster consisted of a group of graduate students and one or two designated senior faculty, as well as junior faculty and post-docs, and included graduate students not connected to EDGE. Mentoring Clusters usually consisted of a dozen or so participants from several institutions. The primary goal of each cluster was to bring women mathematicians (often including statisticians) together a few times each year to discuss the concerns of students and receive advice on teaching, research, and personal or community issues. In some clusters students presented their research to receive input from the group. Some clusters planned events such as a one-day symposium or an outreach project or joined other local groups in doing the same. Clusters were established in six geographical regions: Southern California, Georgia, Indiana, North Carolina, Iowa, and the mid-Atlantic region. A seventh cluster was based on a common passion for mathematics education. Clusters were successful due to the extraordinary commitment of the senior women mathematicians and statisticians, several of whom were past faculty, speakers or local coordinators of the EDGE Program.

Through these efforts to provide more direct mentoring, several regional research symposia and other outreach activities have been organized, inspired, and often co-sponsored by Mentoring Clusters. Early on, a one-day Women in Math Symposium (WIMS), which emerged as a co-sponsored standard activity of the Southern California Mentoring Cluster, included a keynote address, opportunities for women graduate students and faculty to offer short research talks, and dedicated time to collaborate on a research problem. In 2017 the 10th Annual Symposium for Women in Mathematics in Southern California was held with other funding and in cooperation with AWM. The first mid-west WIMS, held at the University of Illinois-Chicago in 2013 gives credit to the "successful WIMS held in Southern California" for its organization. The one-day North Carolina Symposium for Women in Mathematics and Statistics, was co-sponsored by the North Carolina Mentoring Cluster in 2011. Other clusters, including those in Indiana and Georgia, joined local efforts to host lectures by women mathematicians. The Iowa Cluster organized a one-day conference for undergraduate women in mathematics and statistics to encourage preparation for graduate school. These one-day regional symposia and other gatherings are intended to strengthen networks, encourage collaborations, and foster mentoring relationships within a particular geographic region.

Feedback from the EDGE mentoring clusters indicated a need for continued direct interaction between women mathematicians at all stages of their careers. Reports from the clusters, describing the responses of students, suggested that they were very effective in providing critical support to graduate students. Among the most active is the North Carolina cluster in which every woman in the original cohort earned the doctoral degree; it currently continues with a new cohort of graduate students and three committed senior women from three institutions. The Iowa Cluster, which began in 2010, inspired other local mentoring efforts and currently continues with local support.

20.4 EDGE Participant Statistics: 1998–2016

At the time of this writing, 71 EDGE participants have earned doctoral degrees, an indication that the primary goal of the program is being achieved. Intertwined with that goal is a focus on diversity. From its very beginning in 1998, the EDGE Program has been characterized by its commitment to diversity among participants, mentors, faculty, and staff. Of the 243 EDGE participants from 1998–2016, 117 women, or just over 48%, were from groups underrepresented in science and mathematics. According to NSF criteria, underrepresented groups include Alaska Natives, Native Americans, African Americans, Hispanics, Native Hawaiians, and other Pacific Islanders. Among EDGE faculty and graduate student mentors, 52% of faculty and 45% of mentors were from underrepresented groups. The eight participants in the first summer session, as well as the 13–15 participants in subsequent summer sessions,[2] added additional diversity to the program, including economic, geographic, and first-generation-college status.

Time-to-degree attainment varies for different individuals and is sometimes prolonged for women who seek to balance work and family life during graduate

[2]The phrase "subsequent summer sessions" refers to subsequent years other than 2007, a year when there was no summer session and no new participants.

school. In acknowledgement of this nonlinear trajectory, the academic attainment of EDGE participants from 1998–2009 is presented here in order to gain perspective on the long-term progress of the EDGE Program. Of the 134 women who entered the EDGE program during 1998–2009, 49% were White, 42% African American, 6% Latina/Chicana, 2% Asian, and 1% other. As of June 2016, 67 of the participants in this group had earned doctoral degrees, almost all in the mathematical sciences. At least 85% of EDGE participants earn at least one graduate degree. As would be expected, most participants entering graduate programs from 2010 to 2016 have not yet earned doctoral degrees and so no analysis is included for this group.

The necessity for a program that supports all women and yet targets the inclusion of women from underrepresented groups can be seen in the following data, based on AMS Annual Surveys [6]. According to that source, over the five academic years from 2005–2006 to 2009–2010, African American women earned only 3.7% of the doctoral degrees in the mathematical sciences earned by US women. Among those African American women, a noteworthy 27% of them were participants in the EDGE Program [4]. Within the EDGE cohorts, success in earning a doctoral degree varied along racial lines. That is, in the total of cohorts prior to 2010, where 50% have earned the doctoral degree, 59% of Caucasian participants and 41% of participants from underrepresented groups have achieved this initial goal. Some others are still matriculating.

Of course, statistics concerning degree attainment among EDGE participants tell only one part of the EDGE story. In the sections that follow, participants and the leadership reflect on the benefits of the program and its impact on the larger mathematics community.

20.5 EDGE Participants' Viewpoints: Coming of Age Mathematically in a Supportive Environment

A distinguishing feature of the EDGE Program is that, after the four-week summer session, participants remain engaged with the program. They become members of a community that mentors them throughout graduate school and beyond. The EDGE PhD survey [3] provided an opportunity for past participants with earned doctoral degrees to discuss the impact of the EDGE program, including the summer session and the continuing community, on their success and development. This survey does not capture the voices of past participants who left or remain in the PhD pool, including many with earned Master's degrees. Nonetheless, EDGE PhD recipients have important insights to share about the impact of the program on their success.

The racial composition of the 36 EDGE PhD survey respondents—21 (58%) white and 15 (42%) from underrepresented groups—approximated that of the then-total EDGE participant group. Of the survey respondents, 73% were college faculty, 17% were in post-doctoral positions, and 10% were employed outside of academia.

Survey respondents reported that both the academic enrichment and the support and mentoring network that the EDGE community provided contributed to their academic success. They identified the following program components as either "somewhat beneficial" or "very beneficial" to their academic success: (For each item below, the percent of respondents that chose "very beneficial" is given. A third option of "not beneficial" was not chosen by any respondent for any item below.)

- The algebra and analysis courses of the EDGE summer session. (61%—very beneficial)
- Problem sessions conducted by advanced graduate student mentors. (84%—very beneficial)
- Planned social activities, including special weekly dinners. (71%—very beneficial)
- Diversity of the students and staff. (81%—very beneficial)
- Annual Reunion Weekend/Conference. (87%—very beneficial)
- Informal, unplanned activities with other EDGE participants. (79%—very beneficial)

Together these program components provided early exposure to the rigor and pace of graduate school and increased the students' knowledge and confidence in key first-year courses, thereby easing the transition to graduate school. Looking beyond the first year, the foundation was established through EDGE for networking throughout graduate school and into the early careers of participants.

Participants in each summer session had different experiences since each year brought a different faculty, staff, and set of graduate student mentors, and a bonding of peers that was unique to that group. Nevertheless, most respondents rated their engagement with advanced graduate student mentors (81%-very beneficial) as one of the most valuable components of the EDGE Program. The graduate mentor problem sessions and their on-site housing provided time to collaborate on faculty-provided problems, as well as to engage in informal discussions about graduate life.

Some of the most compelling survey responses spoke to the value of the EDGE environment and culture, which respondents described as:

- Nonjudgmental.
- A setting in which students share in a common difficult experience.
- A climate in which students are comfortable revealing vulnerabilities.
- A space in which one's ability to succeed in mathematics is not questioned.
- An environment that is absent of a recurring need to prove oneself.
- A "safe haven" during academic difficulties or periods of self-doubt or disillusionment.

With regard to mentoring, more than half of respondents reported being mentored by another graduate student from EDGE or from their graduate programs, receiving both practical advice and general encouragement. More than two-thirds reported mentoring other graduate students, often out of a desire for others to have a better experience than the mentor. In sum, respondents indicated that they benefited from

Table 20.1 Population Percentages of US Women vs. Percentages of US Women Mathematics Doctoral Recipients [1, 9]

	Percentage of total US population in 2014	Percentage of US citizen mathematics doctoral recipients in 2014	Percentage of all mathematics doctoral degrees awarded in US in 2014
All Women	50.8%	28%	13.3%
Black/African American Women	6.5%	1.1%	0.5%
Hispanic/Latina Women	8.6%	0.5%	0.3%
American Indian/Alaska Native/ Pacific Islander Women	0.5%	0.4%	0.2%
Asian Women	2.8%	2.5%	1.2%
White Women	31%	21.5%	10.3%
Multiracial (not Hispanic) and Other	1.0%	1.7%	0.8%

exposure to women who were at different stages of their mathematical trajectories through both formal and informal contacts.

Thus far, we have summarized responses from the total group of EDGE survey respondents. However, the data suggest that persistence and degree achievement rates among United States graduate students in mathematics doctoral programs vary by both gender and race, with underrepresented women faring far worse than other women. According to AMS Survey data [9], women US citizens from underrepresented groups earned a total of 19 mathematics doctoral degrees in 2014, while White women earned 198 and Asian women earned 23. Overall, 28% of the 920 doctoral degrees awarded to US citizens that year were awarded to women. However, US women were awarded only 13.3% of all mathematics doctoral degrees awarded by US institutions that year. The difference in these numbers is a result of the fact that non-US citizens earned 52% of the mathematics doctoral degrees awarded by US institutions in 2014.

Table 20.1 compares degree awards to the prevalence of each group of women in the US population. While underrepresented women make up 15.6% of the population, they earned only 2.1% of the doctoral degrees in mathematics awarded to US citizens, and only 1% of all mathematics doctoral degrees awarded by US institutions that year.

In 2014, women earned 43% of the Bachelor's degrees in mathematics and statistics [11]. Although down from 46% some 10 years earlier the capacity for women to earn graduate degrees still remains high. Since the percentages of US mathematics doctoral recipients in almost all categories of women in Table 20.1 are far lower than their percentage of the total US population in respective categories and much lower than their share of Bachelor's degrees, one might conclude that women of all races face barriers to persistence and completion of mathematics doctoral degrees. The data also suggest that underrepresented minorities face even greater barriers to persistence and completion than other women. In light of this, we compared EDGE PhD survey results for selected questions using two subgroups: respondents from underrepresented groups (African American/Caribbean, Hispanic/Latina, American Indian/Alaskan Native/Hawaiian) and White/European respondents.

Among respondents to the EDGE PhD Survey [3], 15 women (42%) were from underrepresented groups. The Survey results show that the EDGE-related factors contributing to the persistence of women in earning mathematics doctoral degrees differ by race. In particular:

- Women from underrepresented groups rated certain summer-session activities as "very beneficial" to their academic success more often than white women, including activities such as "working with faculty" (77% versus 47%), "interacting with guest speakers and visitors" (77% versus 21%), and "planned social activities" (85% versus 61%). White women rated the summer session academic components of the program as "very beneficial" to their academic success more often, including problem sessions (69% versus 95%) and courses (58% versus 63%).
- Women from underrepresented groups rated some post-summer-session interactions as "very beneficial" during graduate school more often than white women. These include "contact with EDGE instructors and staff" (85% versus 56%) and "continued contact with other mathematicians met through the EDGE Program" (92% versus 61%).

In general, access to a professional network was considered one of the most important benefits of the EDGE program by women of underrepresented groups.

Historically, "isolation" has been a key barrier to the success of African Americans in mathematics doctoral programs. Bozeman [2] observed that many of the early African American women enrolled in doctoral programs in mathematics lacked a peer group with whom to share ideas and problems, did not realize that others were studying as intensely as they were, and lacked access to the camaraderie and academic discourse found in study groups.

The reflections of women participants in the EDGE PhD Survey suggest a need to expand the meaning of "isolation" in departments so that it applies to the case of mathematics graduate students that have a "lack of access," not only to the relevant peer group, but also to the culture, strategies, professional network, and all relevant information that is crucial for success in any mathematical or scientific discipline to which the student aspires.

20.6 EDGE Directors' Viewpoints: Developing Emerging Leaders

The impact of the EDGE Program reaches beyond its beginning graduate students. Advanced graduate student mentors in residence during the summer session gain leadership experience while juggling their own responsibilities, including exam preparation and research. These mentors often see themselves in a new, satisfying role of serving as liaisons between faculty and beginning students. From 1998 through 2013, 34 different advanced graduate students served in this role, some for multiple years. Among that group, 85% persisted to the doctoral degree. Several others from later years are still active in their graduate programs. In recognition of EDGE's commitment to diversity, half of these graduate mentors were members of underrepresented racial and ethnic groups. Some who began their association with EDGE as beginning graduate students or as graduate mentors later returned as EDGE faculty members or as local host coordinators for the summer session.

EDGE's success depends heavily on mathematics faculty who travel from their home institutions to join two-person teaching teams for the algebra and analysis summer courses. In addition to providing instruction, they collaborate with advanced graduate mentors to strengthen the program as a whole. Many solidify their connection to the EDGE community by continuing to mentor students long after the summer session ends. Through 2016, 39 different faculty members from almost as many institutions have taught the basic courses while many others offered mini-courses or gave research talks.

The EDGE leadership has provided outreach beyond the students and faculty involved in the summer sessions. For example, in response to the NSF's urgent call for "broadening participation" in its programs and activities, EDGE sponsored a national forum at the Mathematical Sciences Research Institute (MSRI) in 2008 titled, "Promoting Diversity at the Graduate Level in Mathematics." The conference served as "a call to action, a challenge, and an appeal to universities across the U.S. to address the issue of diversity in their graduate mathematics departments." By design it provided an opportunity for focused exchanges among representatives of research universities, comprehensive universities, small colleges, and graduate students. Conference Proceedings [7] containing resulting ideas and recommendations were published and are available through MSRI.

The EDGE Directors have identified numerous "EDGE Second Effects," instances of EDGE alumnae developing programs or serving in roles that support the next generation of women in mathematics. EDGE alumnae have assumed leadership roles in developing a national professional development symposium for women completing mathematics PhDs, organizing an annual mathematics and science conference for African American girls, providing a keynote speech at a national mathematics conference, serving as an AMS Congressional Fellow, delivering a mathematics-themed TED talk that has been viewed over one-million times, leading a teacher development program, assuming leadership roles in professional associations, and serving on a governor's state STEM education task force. Further, EDGE alumnae and community members have organized special sessions at the Joint Mathematics Meetings, the Association for Women in Mathematics Research Conference, and the International Mathematics Congress in Vancouver. Many of them are also making a difference as innovative faculty members in the nation's colleges and universities. The EDGE Second Effects advance a philosophy of diversity and inclusion that is changing the composition of the next generation of mathematicians to yield greater participation by all segments of society.

The EDGE summer session is hosted at a variety of colleges and universities in order to establish a national profile among prospective students, involve local personnel throughout the country, and to more broadly engage the mathematics community. Spelman College and Bryn Mawr College hosted the first four summer sessions which were coordinated by the EDGE founders. Subsequent EDGE summer sessions (with local coordinators listed in parentheses) were held at Pomona College (Ami Radunskaya), North Carolina A&T State University (Janis Oldham), North Carolina State University (Ruth Haas, A. Loek Helminck and Kim Weems), Harvey Mudd College (Talithia Williams), Florida A & M University (Roselyn Williams), Howard University (Talitha Washington), Purdue University (Alejandra Alvarado and Edray Goins), New College in Florida (Eirini Poimenidou), and Spelman College (Fred Bowers and Yewande Olubummo). In addition to the local coordinator, each summer session benefited from the host school's support necessary to house the Program, insure the well-being of participants and visiting faculty, and meet special needs of the Program.

In 2011 Hughes and Bozeman passed the leadership of the EDGE Program to the current co-directors, Ami Radunskaya (Pomona College) and Ulrica Wilson (Morehouse College). Both Radunskaya and Wilson emerged from this evolving EDGE community of students, mentors, and faculty. Before leading the Program, Radunskaya was a member of the first analysis teaching team, taught for 11 years, and mentored scores of students. Wilson first engaged students as an advanced graduate mentor for several years and, after earning the doctoral degree, returned as an algebra instructor for five years before leading the Program. Their commitment to teaching and mentoring is woven into the EDGE program fabric. In 2014, under the leadership of Wilson and Radunskaya, EDGE reached its "50th Ph.D. milestone." In addition to creating additional support avenues for graduate students and emerging professionals, the current leadership has given oversight to the creation of The EDGE Foundation, a 501(c)(3) entity. The Foundation Board works with the co-directors to oversee program activities, including planning, marketing, development of policies and procedures, and fundraising. The goal of the Foundation is to ensure the continuation of the EDGE Program and its legacy of supporting women mathematicians.

20.7 Final Words: A Call to US Graduate Mathematics Departments and Thoughts on Diversity

The EDGE Program was not the first to identify and address barriers to success for women and underrepresented groups in doctoral programs in mathematics and science. In the 1998 report of her American Association for the Advancement of Science (AAAS) Presidential Lecture, Voices from the Pipeline [10], Sheila Widnall asserted that "a reasonable objective for the education of women and minority students is that they have a fair chance to succeed in graduate school; that the feedback loop of lowered expectations based on sex or race, leading to lowered self-image and finally to lower performance, be broken by conscious action by faculty and students." According to the 1984–85 AMS-MAA Survey data, a few years prior to Widnall's assertion, only 20 percent of mathematics doctoral degrees awarded to US citizens were awarded to women. None, however, were African American women that year. (A total of 7 African-American women earned mathematics doctoral degrees over the 5-year period centered on 1984–85.)

Dr. Etta Falconer, a lifetime advocate for women and minorities in science and mathematics and recipient of the Association for Women in Mathematics Louise Hay Award, among other prestigious awards, put forth her own suggestions for integrating minority students into mathematics departments. Among her many suggestions, she wrote in [5];

> Graduate minority students need a proper dissertation advisor, a proper committee, the right courses, discussions of mathematics over coffee, the goodwill fostered by attending the department mathematics talks, a knowledge of actions which promote and those which retard progress, healthy research connections with faculty, help in submitting a paper to a journal, and suggestions of mathematicians to send advance copies of a research paper. In other words, they need the same things that have proven effective in moving other students into mathematics research.

The research component of the EDGE Program is a modern-day effort to build upon the work of Etta Falconer, Lee Lorch, Mary Gray, and many others who worked tirelessly for decades to diversify the mathematics and scientific communities. The voices of the women who succeeded in earning doctoral degrees while being mentored through EDGE provide guidance that directs us into the future.

Any organization external to graduate mathematics departments will be limited in effecting national change. It is, therefore, incumbent upon US graduate mathematics departments to support gender and racial diversity by adopting and adapting components of EDGE and other programs that have proven successful. The following are recommendations for US departments of mathematics that wish to diversify their graduate programs:

1. Encourage admission committees to consider personal attributes necessary for success. These attributes may include evidence of leadership, persistence, and grit, in addition to grades, and faculty recommendations. Evidence of these personal attributes may be evaluated in either academic or nonacademic settings.

2. Offer an on-location, short, intensive summer bridge program for entering mathematics graduate students. Such a program may serve students entering your program or other regional mathematics graduate programs. In the event that spots are limited, preference might be given to students from small schools with limited exposure to advanced or graduate courses. The summer bridge program may include coursework that connects undergraduate and graduate mathematics and activities that introduce students to the culture, rigor, pace, study expectations, and challenges of mathematics graduate school. The staff should include faculty and advanced graduate students, with attention to diversity.
3. Provide formal and informal mentoring and networking opportunities during and after graduate school. Graduate mathematics departments should reach out to graduate women and students from underrepresented groups to help develop professional skills that extend beyond the classroom and teaching assignments.
4. Promote a culture of agility and flexibility among mathematics graduate program faculty. This culture of agility may respond to emergent student needs, particularly among women and those from underrepresented groups.
5. Recruit and retain women faculty and faculty from underrepresented groups in the Mathematics Department. The results may model an inclusive mathematics community that offers a diverse community of role models for a diverse community of mathematics graduate and undergraduate students.
6. Design and offer activities that guard against the “isolation” of students from underrepresented groups. Help student to become integrated into their departments and also “gain access to the profession” they wish to enter.
7. Enlist advanced mathematics graduate students to mentor new mathematics graduate students. This recommendation provides not only mentoring for incoming students but also professional experience for advanced graduate students. Ensure that women and students from underrepresented groups are aware of opportunities to have mentors as well as to become mentors.
8. Work to foster a diverse community—not just a diverse collection—of mathematics faculty and students in a graduate mathematics department. This may, on occasion, require guidance from a sociologist or psychologist who is prepared to assist students and faculty in engaging in difficult dialogues.

When the EDGE Program was founded by Bozeman and Hughes to help women make the transition from college to doctoral programs in mathematics, diversity was a central goal of the participant selection process. As the Program evolved, steps were taken to ensure that EDGE had more than just diversity in numbers. Today, EDGE is a vibrant, ever-expanding, and diverse community of mathematics graduate students, doctoral recipients, and faculty that emphasizes collaboration. It enables community members to value both the comfort a community offers and the difficult conversations that sometimes ensue. EDGE today is a diverse community of individuals who mentor, advise, and collaborate across racial and cultural boundaries in ways the founders never imagined.

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We thank the many faculty and graduate mentors who we do not have space to identify by name. We express sincere appreciation to Ami Radunskaya and Ulrica Wilson who accepted the leading roles as co-directors when the founding directors retired. Finally, we thank all of the EDGE alumnae who continue to inspire us every day.

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Chapter 21
The Daughters of Hypatia: Dancing the Stories of Women in Mathematics

Karl Schaffer

Abstract *The Daughters of Hypatia: Circles of Mathematical Women* is a 90-minute contemporary dance performance, featuring four women dancers, that recounts intriguing stories from the lives of women mathematicians throughout history, representing an attempt to bring mathematical women into popular culture. *Daughters of Hypatia* integrates theatrical storytelling, multimedia displays, engaging audience interactions, and choreographic patterns suggestive of the women's mathematical work. The show includes autobiographical statements and dances by the performers themselves and the concert is now presented in a variety of formats, including school performances of 40 to 60 minutes, sensory-friendly performances, and full-length public performances up to an hour and a half. In this chapter, we summarize the experiences of the author's dance company, beginning in 2011, in developing and performing this as a touring concert. In addition, we analyze audience responses, describe issues confronted during development of the work, and consider plans for future performances.

Keywords Dance • Choreography • Performance • Hypatia • Mathematics

21.1 Introduction

The Daughters of Hypatia: Circles of Mathematical Women is a 90-minute four-woman contemporary dance performance celebrating women mathematicians throughout history. Dedicated to the foremothers of mathematics as well as to their leading contemporaries, the concert is designed to inspire as well as educate audiences with dramatic stories of the passion and determination that women have used to overcome barriers to their participation in the world of mathematics. The performance integrates theatrical storytelling, multimedia displays, and engaging audience interactions as the dancers recount intriguing stories from the women's lives and perform patterns suggestive of their mathematical work. This chapter tells

K. Schaffer (✉)
De Anza College, Cupertino, CA, USA
e-mail: karl_schaffer@yahoo.com

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Fig. 21.1 Dancers in *Daughters of Hypatia*. Photo by Steve DiBartolomeo

the story of the dance group directed by the author as I began in 2011 to work with the dancers to develop and perform this concert [17]. It examines justifications for the point of view of the work, describes issues confronted during development of the show, reviews audience responses, and considers plans for future performances.

The title of the concert derives from Hypatia, the earliest known female mathematician and a leading intellectual in ancient Alexandria. The performance includes stories of women mathematicians of the last several hundred years, as well as contemporary women mathematicians. Contributions to the show include a video dance and monologue by sarah-marie belcastro,[1] a skit on micro-inequities by Sue Geller, live projection of video mosaics of dancers with software created by Kevin Lee, tessellation designs by Marjorie Rice, autobiographical statements about mathematics by the four dancers in the show, and musical compositions by mathemusician Vi Hart, women's world music choral ensemble Zambra, and composer Victor Spiegel.

21.2 The Need for New Forms of Historical Storytelling

21.2.1 Addressing Stereotypes, Barriers, and Bias

Daughters of Hypatia shines a light on the historical bias against women mathematicians and highlights the importance of positive role models for women mathematicians, the diversity of women mathematicians, and the persistence and passion which fueled the ability of these mathematicians to overcome societal and professional barriers. The importance for including these elements is described below.

[1] All representations of names in this article are consistent with the preferences of the individuals.

Women's contributions to mathematics have historically been undervalued. For centuries women were denied access to the study of mathematics, their intellectual powers denigrated, and their accomplishments downplayed. However, women, often self-taught, made marvelous mathematical discoveries, even when obstacles were placed in their way. Many women mathematicians disguised their identities in order to do mathematics: Émilie du Châtelet dressed as a man in order to attend lectures [16], Sophie Germain published under a male pseudonym [31], and Emmy Noether gave lectures under the name of a male colleague [22]. These stories from the past are inspiring, yet sobering.

Daughters of Hypatia addresses the variety of societal barriers encountered and then overcome by the women highlighted, because bias against females doing mathematics is still discouragingly prevalent. This bias may account for pessimistic attitudes among young women about their participation in mathematics. For example, in a recent book mathematical researcher and educator Jo Boaler quotes a student who described her feelings about her mathematical ability: "…I watched it on 20/20 [a television current affairs program] saying girls are no good, and I thought—well if we're not good at it then why are you making me learn it?" [2, p. 24].

Nature versus nurture questions still arise, as Boaler noted when she warned that "[t]he tendency to focus analyses of underachievement upon categories of students, rather than the environments that coproduce differences, is not unusual in equity analyses" [2, p. 22] and that "…the prevailing idea that girls are mathematically inferior often derives from the findings of equity researchers" [2, p. 24]. Lynda Wiest reiterates this point of view, writing that "[b]oth females and males should understand familial, societal, and institutional barriers so that they do not perceive women's absence as a lack of ability" [33, p. 162]. A study published in 2014 by the National Academy of Sciences reiterates the prejudice that still exists, noting, "[w]hen employers had no information beyond appearance, they were twice more likely to choose male candidates than female candidates" [26, p. 4405].

The belief that because of biology, women and girls have less ability in mathematics compared to men is also countered by a 2012 research study by Kane and Mertz [13]. Summarizing their results, Mertz said, "[t]his is not a matter of biology: None of our findings suggest that an innate biological difference between the sexes is the primary reason for a gender gap in math performance at any level. Rather, these major international studies strongly suggest that the math-gender gap, where it occurs, is due to sociocultural factors that differ among countries, and that these factors can be changed" [32].

Dance and theater are able to communicate these ideas about discrimination and tales from the past in surprisingly visceral as well as intellectual ways. Dance often engages audiences by generating immediate kinesthetic rapport, while theater adds dramatic, humorous, or even ambiguous elements. By combining these components with multimedia (images of mathematical concepts, projections of women mathematicians, mathematical artwork), the overall performance becomes layered and rich, reaching a variety of audiences in unexpected ways.

Of course, a few stories about successful women mathematicians might simply be taken as lonely exceptions to the biased "rule" that women cannot do mathematics. Therefore, one dance features large numbers of names and photos of women of all ethnicities and ages who have become successful mathematicians as a counter to this assumption.

These historical role models are definitely necessary for breaking gender stereotypes. In her book *Changing the Faces of Mathematics: Perspectives on Gender*, Leah McCoy states that "[b]ecause female students are not aware of female mathematicians and scientists, they may internalize a belief that mathematics is not appropriate for women" [18, p. 125]. An American Association of University Women study of the underrepresentation of women in science, technology, engineering, and mathematics careers recommended that in order to combat stereotypes, it is important to "[e]xpose girls to successful female role models in math and science. Exposing girls to successful female role models can help counter negative stereotypes because girls see that people like them can be successful and stereotype threat can be managed and overcome" [10, p. 42].

21.2.2 Celebrating Role Models and Stories of Success

Because *Daughters of Hypatia* is often performed for school age audiences, it is important to pay attention to the power of role models. A 2013 research study on the importance of role models for young women concluded that "[w]hat seems to be missing are good role models that could act as inspiration and source of information and guidance, and offer a glimpse into the reality of being a female employed in the field of science and/or technology" [6, p. 1]. As a result, "[s]cience is often rejected as a career choice due to limited information available and positive role models to encourage young girls in participating" [6, p. 1]. The authors also warned against "the presentation of role models resembling the superwoman, an unrealistic portrayal which can restrict the role models [*sic*] potential to act in an influential manner" [6, p. 10]. Paying attention to these warnings, I include pictures of the women highlighted in the show at various ages and from different ethnic groups, all eager to tell their stories to the world.

Daughters of Hypatia is not designed as only an educational outreach show for young students. The full-length version is specifically designed for and has been popular among adult viewers, including those in math and the sciences. This is important, as misperceptions survive in the general adult public, and even among those involved in careers as mathematicians. For example, in an article in the *Atlantic Monthly*, Jane C. Hu pointed to the continuing prevalence of stereotypes and discrimination against women involved professionally in the field of mathematics [12].

I also try to show the process and persistence of women who become mathematicians. Mathematician, data scientist and blogger Cathy O'Neill points out that "... it is possible to address stereotype threat directly, which won't solve everything but will go a long way. You do it by emphasizing that mathematical talent is not inherent, nor fixed at birth, and that you can cultivate it and grow it over time and through hard work" [24].

Two recent studies suggest that dance may also be a very appropriate medium for delivering these messages in our performance, as it appears that dance appeals to and connects with those who do not occupy the highest success brackets in mathematics with a wide range of people, including those traditionally underrepresented in the mathematical sciences. A 2010 study of 3600 young people ages 12 to 19 found that 34.8% of girls and 8.4% of boys make dance a regular part of their physical activities [1, 25]. The study also reported that African American and Hispanic girls participated in dance at higher levels than white girls. Among boys, twice as many African American and Hispanic males participated in dance as did whites, and rates were higher for low income boys than those in high income brackets. Another study found that the arts in general may be effective in increasing gender equity in math and the sciences [15].

21.3 Background and Development of the Daughters of Hypatia

21.3.1 Step One: Men Dancing About Mathematics!

The story of the creation of this work really begins many years ago with a dance performance designed to entertain and intrigue audiences with the ubiquity and enjoyment of mathematics. In 1990, Erik Stern and I created a duet show, *Dr. Schaffer and Mr. Stern: Two Guys Dancing about Math*.[2] This concert centered around two characters, each of whom always wants to be correct: one from a purely rational and scientific point of view, the other from the more emotional and thoughtful perspective of experience and intuition. As the show progressed they argued about whether or not mathematics may be found in everything people do, for example while clapping rhythms, finding ways to shake hands, tap dancing, manipulating a basketball in space, or using symmetry in a dance. At that time, two guys discussing mathematics was certainly the norm, but two men dancing about

[2]This show provided an arts and science outlet for my background as a mathematician and for Erik's as an undergraduate biology major with interest in math. Both of us had been dancing and choreographing professionally for a number of years and had co-directed a dance company, which we still run, since 1987 [28]. That company, the Dr. Schaffer and Mr. Stern Dance Ensemble, operates under the umbrella of our non-profit organization MoveSpeakSpin, which is also the company name we use for *Hypatia*. Stern and the author have pioneered the integration of dance and mathematics in many performances and in the classroom and dance studio. As Teaching Artists with the Kennedy Center for the Performing Arts we travel frequently to teach workshops on connecting math and dance.

mathematics was definitely unusual! We performed this show over 500 times all across North America, in theaters and schools and at festivals and conferences, until 2003.

Interestingly, *Two Guys* exhibited an ironic sense about male predominance with its use of the word "Guy," which in the 1990s became a common satirical poke at male predilections in a variety of media. Other popular references to "Guy" included Comic Book Guy, a character from *The Simpsons* who runs a comic book store; the science program *Bill Nye, the Science Guy*; Guy Noir, the comedic private detective from *Prairie Home Companion*; and *Family Guy*, Fox's adult cartoon sitcom.

21.3.2 Step Two: Weaving Stories of Women Doing Mathematics into Existing Performances

The inclusion of stories of women into our dance performances happened in stages. Having discussed Galileo's investigations of motion under gravity before and after performing a basketball dance set to music in *Two Guys*, we also wanted to tell the story of a woman who subverted expectations to do mathematics. As a result, we created a segment of the *Two Guys* show telling the story of Ada Lovelace's invention of computer programming. Several years after we stopped performing *Two Guys*, we added a short biographical dance about the life and work of Sonya Kovaleskaya to another show, one still in our repertory, called *The Secret Life of Squares*. That dance sequence uses a basketball manipulated by longtime company dancer Saki in rhythmic gymnastics fashion as metaphor for Kovaleskaya's work on the rotation of solid bodies. A few years after that, I wanted to see how a piece focusing on several short danced stories of women in mathematics might play with audiences, so I wrote text for and choreographed a sequence of such movement stories entitled "Circles of Mathematical Women" as part of a longer concert in 2011. The stories were perhaps a predictable group: Hypatia, Maria Agnesi, Émilie du Châtelet, Sonya Kovaleskaya, Sophie Germain, Florence Nightingale, and Emmy Noether. These were followed by a movement piece in which the dancers recited in rapid fire the names of prominent women mathematicians throughout history as the women's pictures appeared projected behind the dancers.

21.3.3 The Importance of Authentic Voices

As a male directing a dance concert about women mathematicians, I have been aware from the beginning of the danger that those of us who are allies in such struggles might inadvertently contribute to the problems we are trying to address. This might happen by presenting or highlighting inauthentic voices, thus robbing the women mathematicians who are our focus of their agency. Several examples in the mainstream media come to mind: The film *Mississippi Burning*, about the investigation of the murders of three civil rights workers and directed and written by white males, which presents white FBI agents as the true heroes of the civil rights movement [9]; the film *The Imitation Game*, which falsely depicts mathematician and World War II code-breaker Alan Turing as cowed into treasonous complicity with Soviet spying due to his fear of being exposed as homosexual [19]; the film *Hidden Figures*, written and directed by whites (unlike the book on which it was based) about African American women mathematicians working in the space race, in which a white supervisor, rather than the black women who are the movie's protagonists, is fictionally shown desegregating the restrooms [29].

Given these concerns, as the show has developed I have sought feedback from women active in feminist causes and have included a number of direct statements and work of contemporary women in mathematics and dance, as discussed in Section 21.5. I have often wondered how such a concert might have developed if created by women mathematicians who are also dancers, and it seems to me that such a show might be developed in different directions and display other aspects of depth, nuance, and personal experience. But I also have reflected on how most of us involved in social justice issues spend much time speaking and acting in support of oppressed groups that do not include ourselves, and these acts as allies are necessary to provide a supportive voice and bring awareness to these issues.

21.3.4 Step Three: A Full-Length Performance Celebrating Stories of Women in Mathematics

Encouraged to continue work on this concert by our dance company's long-time supporters and cognizant of the ever-present need for public performances celebrating women's struggles and achievements in the sciences, we continued to develop the show. Our first full-length version of *Daughters of Hypatia* opened in 2012 at the studio/theater Motion Pacific, and then for a nine-day run in 2014 at West End Studio Theatre, both in Santa Cruz, CA. The latter series included a shorter version for students and a longer evening length version for the general public. In 2014 and 2015, the company began touring the show seriously, with a performance for Sonya Kovalesky Day in Fresno, CA and a four-day residency at the Alys Stephens Center for the Performing Arts in Birmingham, AL. In Birmingham, we were hosted by Kimberly Kirklin, the Stephens Center's Director of Artplay. In addition to shorter versions of *Hypatia* for students and the longer evening length version for general audiences, Kimberly arranged a special lunchtime performance in one of the University of Alabama's Hospitals, and a "sensory friendly" performance for families with children with special needs. It was an important development for us to re-organize the work for these performances. And at one performance in Birmingham in 2015, local teacher Jim Wilder filled the lobby with tables of mathematical games and puzzles, overseen by a group of his sixth-grade students (Figure 21.2).[3]

[3] This was part of the Gathering 4 Gardner's Celebration of Mind, which occurs around the world every October in honor of Martin Gardner's work popularizing mathematics [7].

Fig. 21.2 Math games at Alys Stephens Center for the Performing Arts in Birmingham, Alabama. Photo by Clark Scott

Although initially the dances and stories in *Daughters of Hypatia* focused on women of European descent from the 1700s and 1800s, recent additions to the show include contemporary and mathematical women of non-European origin, highlighting their struggles and also drawing out the ways that mathematical thinking is embedded—and often hidden—in craft and art work such as fabric arts, dance, and language arts.

The show now also includes danced autobiographical movement poems by the performers themselves as they tell, in words and movement, stories about how their participation in the project has illuminated their own relationship to mathematical thinking and how they find this in the ways in which they move in time, space, and pattern. I have also recently created several versions of the performance for schools and a lengthy accompanying study guide that addresses arts education and gender issues and makes connections between the school curriculum and the work of women mathematicians featured in the show. Overall, this concert represents one attempt to bring mathematical women into popular culture.

21.4 Performance Details

The format of *Daughters of Hypatia* is a series of over twenty short sections composed of short historical vignettes interspersed primarily by dances to musical scores or audience interactions. The historical sections are performed by dancers who tell the stories of important women mathematicians while they simultaneously execute energetic choreography, either as solos or with the other dancers performing as chorus. Dance that includes spoken word is an extremely challenging form that takes theatrical skill, dance expertise, and a great deal of rehearsal!

21.4.1 Creative Contributions: Video Dance, Music, and Humor

Creative contributions to the show include a video dance by dancer and mathematician sarah-marie belcastro. She discusses her life in these realms as well as her work with mathematical fabric arts as she dances in a video projection, while the cast performs the same movements as a chorus downstage of the video. As part of her monologue, sarah-marie says that

> Mathematics and mathematical objects and aesthetics inform my creation of movement, and they inform everything I do. Sometimes I knit or crochet mathematical objects and I am concerned about the symmetries of the stitches . . . Many mathematicians have multiple interests, but in my experience this is true more often for female mathematicians than male mathematicians. This probably reflects the way women and men inhabit our overall culture more than anything else [21].

A humorous skit about micro-inequities by Sue Geller was adapted with her permission. Geller collected and published a number of these skits, some of which were performed at the Joint Math Meetings in the early 1990s [8].

Musical compositions by self-described mathemusician Vi Hart are used in several scenes. Although Hart is best known for her smart and entertaining mathematical videos, she is also an accomplished musician and composer. Mathematical songs by Zambra, with whom we have collaborated on a number of shows, are used throughout. Two of their mathematical songs we use in *Daughters of Hypatia* were originally created for the 2009 show *Harmonious Equations*, directed by Keith Devlin, for which we created accompanying dances [5]. Other songs by Zambra are used to accompany a video tessellation dance, which we will explain in Section 21.7.

In 2015, for the Birmingham residency and also for a performance at De Anza College for students and faculty, I worked collaboratively with the dancers to extend the stories to include people of color and to include several new sections, in order to bring the content more up to date and expand its point of view. I included short autobiographical statements by the dancers and made a short dance to an African musical score highlighting the use of mathematics in traditional textile designs around the world (Figure 21.3).

21.4.2 Depictions of Diversity

As noted in Section 21.3, the performance now includes depictions of a diversity of women, including Vivienne Malone-Mayes, Julia Robinson, Marjorie Rice, Karen Uhlenbeck, and Maryam Mirzakhani. We also mention and display the iconic photo showing Maryam Mirzakhani at the Fields Medal Ceremony presided over by Park Geun-hye, the first woman president of South Korea, and Ingrid Daubechies, the first woman President of the International Mathematical Union [3].

Fig. 21.3 Dancers performing "Weavings," Alys Stephens Center, Birmingham, AL, 2015. Photo by Scott Clark

The story of Vivienne Malone-Mayes is particularly poignant, and that dance section includes physicalizations of the conflict and struggles she experienced. While one dancer recounts her story, others perform choreography evocative of a person breaking through barriers. Although Malone-Mayes had chaired the math department at a traditionally black college, when she moved to the University of Texas at Austin (UT Austin) to work on her PhD she was denied a teaching assistantship. When she discovered that mathematics faculty and graduate students there met regularly at a well-known local café, she attempted to join them but was denied entrance because she was black. However, at the time a picket line protesting segregation at that café had formed, so she joined that instead! One of the renowned mathematicians at UT Austin at the time was R. L. Moore, expositor of the "Moore Method" in which students develop and prove important concepts and theorems on their own rather than reading them in texts or the literature. However, he was racist and would not allow her in his classes; as many of his former students and colleagues have attested, he refused to teach black students and thought women inferior [23, 34]. Despite these difficulties, she received her PhD and went on to teach for many years at Baylor University, which had originally refused her admittance because she was black.

21.5 Dancers' Statements

The current set of performers in *Daughters of Hypatia* are a stable and committed group of professional dancers who have all been with the company for a number of years. Their biographies, outlined below, provide important context as they all have a wide range of experiences in the dance world, both as performers and teachers. The monologues they each wrote are revealing; these monologues provide insight into their thoughts about this show and are helpful to understand how we have modified the show, so they are included here. A soft piano score by Hart accompanies these monologues and each dancer dances her own choreography as she speaks.

21.5.1 Saki

Saki has performed nationally and internationally with our local Santa Cruz company and the longer-standing Dr. Schaffer and Mr. Stern Dance Ensemble (DSMS) for 17 years[4]. Saki has also performed contemporary dance, aerial dance, and gymnastics with a variety of San Francisco Bay Area companies, most notably Tandy Beal and Company. She teaches in local schools and studios, and teaches math/dance integration with DSMS on tour. Saki has a BFA in Modern Dance from the University of Utah (Figure 21.4). During the show, she says the following while dancing,

Fig. 21.4 Saki. Photo by Steve DiBartolomeo

[4]This company performs the joint choreography of the author and Erik Stern.

> As performers in this show we've come to think a lot about mathematics. Some of my best early memories are learning origami, weaving, knitting and string figures from my obaa-chan, my grandmother in Japan, and now I see that these were a tactile form of mathematics [performs the string figure, 'Bear Climbing a Tree,' while speaking]. I think I connected with my favorite subjects math and science because of these early experiences. To this day I gravitate towards creating designs [performs the string figure 5-Pointed Star] both in my free time and professionally. I live in the world of dance and love exploring connections with other creative avenues like [performs the string figure Butterfly/Moth] the art of mathematics [21].

21.5.2 Lila Salhov

Lila Salhov received her BFA in dance performance from the Boston Conservatory and danced contemporary, ballet, tap and baroque dance with companies on the East Coast and the San Francisco Bay Area. She now teaches and performs in the Bay Area and has performed with MoveSpeakSpin for seven years (Figure 21.5). In the show she says,

> I always liked math, it was like doing puzzles, but I always thought of it as black and white, right or wrong, and there was a lot of memorization. But now I see it involves much more: imagination, creativity, thinking in new ways, it's a lot bigger. It's in how we subdivide a rhythmic phrase to make a tap dance [she taps], how we organize the dancers in patterns on the stage, how we flow through shapes in space and time [21].

Fig. 21.5 Lila Salhov. Photo by Steve DiBartolomeo

Fig. 21.6 Jane Real. Photo by Steve DiBartolomeo

21.5.3 Jane Real

Jane Real has an MA in Dance and an MS in Elementary Education, has been rehearsal director and performer with Bill T. Jones/Arnie Zane Dance Company, director of the Dance Network of Brooklyn, NY, and has recently performed with Tandy Beal and Company. She has performed with MoveSpeakSpin for seven years (Figure 21.6).

> As a child we just understood that boys were better at math. The stereotypes and the teaching of the subject itself were very limiting. I've never thought of myself as a mathematician, but as an artist. Yet I've come to know that as a dancer, choreographer, and human being we are immersed in a universe of mathematical concepts . . . We live, dream, and exist in it . . . I now have the vocabulary to understand this . . . [21].

21.5.4 Laurel Shastri

Laurel Shastri served 17 years at Ballet Tennessee in Chattanooga, as Associate Director, company dancer, and faculty. She has an MS in Geology from the University of New Mexico and is a teaching artist specializing in integrating dance with diverse subjects such as science and language arts. After moving to California, she joined the roster of teaching artists for the SPECTRA Arts in the Schools Program in Santa Cruz and at the Montalvo Arts Center in Saratoga, CA, and has performed with MoveSpeakSpin for three years (Figure 21.7).

Fig. 21.7 Laurel Shastri. Photo by Steve DiBartolomeo

> I come from an academic family and I always enjoyed math and science. I studied and received a Master's Degree in Geology before I went back to dance. But I had a geology professor who discouraged me, telling me, "Oh, certain people just cannot picture in three dimensions" even though I'd done that all the time in calculus—and as a dancer [21].

21.6 Use of Circular Imagery

Throughout *Daughters of Hypatia* we use circular imagery for a variety of purposes. We refer to some of the historical and mathematical properties of circles or make use of circular props such as oversize hoops, for example, in a duet entitled *A Circle Has No Sides* in which two dancers are bound by one hoop (Figure 21.8); in a short quartet highlighting several women who have worked on the mathematics of Apollonian circles; and in an audience interaction with a circular rhythm cycle.

A number of the historical sections of the show are also drawn together by dances exploring circular motifs, suggesting the circles of support and connection that have nurtured women in this field. Several segments of the show present this idea, sometimes through text spoken by the dancers, sometimes more abstractly through movement imagery. Some of the connections we point out include Julia Robinson's work on the logical foundations of mathematics as exhibited by Diophantine equations; these equations were also the subject of some of Hypatia's writings

Fig. 21.8 Laurel Shastri and Lila Salhov in "A Circle Has No Sides," Alys Stephens Center, Birmingham, AL, 2015. Photo by Clark Scott

as well as Mary Somerville's first paper (Mary Somerville was a mentor of Ada Lovelace). Olga Taussky Todd was an assistant and friend of Emmy Noether's, and Doris Schattschneider wrote the story of Marjorie Rice's discoveries. A number of folk-like dances use circular patterns and imagery to evoke a sense of community and connection. Scott Kim, well-known puzzle designer and math educator and a frequent collaborator in our company's math dance work, described the use of circular themes this way, "*The Daughters of Hypatia* [. . .] cleverly grabs the traditional image of women gracefully dancing in a circle and turns it into a symbol of mathematical power and collegial support" [14].

21.7 Mathematical Elements in the Show

In addition to the biographical and anecdotal stories, we also thought it crucial to discuss or display some elements of the women's mathematical work as danced patterns, through storytelling, multimedia images, or audience interactions.

We use oversize projections of the women highlighted in the show and displays of their work throughout the performance. For example, when telling the story of Marjorie Rice's discoveries of new classes of pentagons that tile the plane, we show her original mathematical diagrams, but also, with Rice's permission, some of the

Fig. 21.9 Dancers Jane Real and Lila Salhov manipulate their projected images created with software by Kevin Lee. Photo by Clark Scott

Escher-like beautiful designs she created based on those tiling patterns.[5] The section on Marjorie Rice is followed by a performance of video tessellations, made up of live mosaics of the dancers created in real time by software developed by Kevin Lee; the tessellation designs are interactively manipulated by the dancers to a score by Zambra (Figure 21.9).

We use the story of Julia Robinson's work on the logical foundations of mathematics as introduction to a delightful audience interaction logic game involving three hats worn by two dancers and one audience member. The game rule, cleverly manipulated by the two dancers, and usually equally cleverly responded to by the audience member, is that the three participants must hold the hats at one of three levels—on the head, at the chest, or by the feet—and no two hats may be at the same level at the same time.

Sophie Germain's story is told by a dancer who periodically interrupts her own storytelling by reciting the next number in an increasing sequence of what are now known as Germain primes, starting with the number 2. To get the next Germain prime in the sequence, one doubles the previous number and adds 1. The dancer is able to time it so that young audience members are able to gleefully shout out the next number in the sequence! Sophie Germain's work on elasticity was central to the construction of the Eiffel Tower. We show photos of that part of the Eiffel

[5] These designs are often left out of discussions about Rice's mathematical discoveries.

Tower displaying the 72 names of scientists and engineers who did scientific work necessary to its construction, which to this day still omits Germain's name.

Emmy Noether's story is accompanied by danced displays of symmetry types, as her theorem explaining the connection between symmetry and conservation laws is described. As in these cases, at all times we attempt to give some indication, either directly or metaphorically, of the mathematical work as well as the life stories central to the project.

21.8 Responses to the Concert

A performance at De Anza College in April 2015, in which students attending were required to fill out a questionnaire in order to receive class credit, provides some insights into how the show is perceived. The 84 detailed student questionnaires we received suggested differences in how female and male students related to different parts of the performance. One question asked, "What section, dance, or story in the performance stood out for you the most? Describe it and explain why." Among the responses, female students gravitated toward the stories of the women highlighted in the show, while males seemed to prefer pieces not referring to gender issues, though there were equal numbers who mentioned the skit on micro-inequities (Table 21.1).

Among the more detailed overall responses by students to the show were those to the question, "Can you relate the performance to your experience with mathematics?" Many brought up gender issues, for example:

- Growing up I know I was not expected to enjoy math or math based careers. While all the women around me were choosing to be housewives or nurses or bakers, I feel that many found it conventional for me to be interested in an accounting future. I relate with the women who defied what was expected of them for the sake of what interested them.
- I am a woman taking higher math classes than usual, although I now feel the world is gradually accepting women as intellectual equals ... the women mentioned were very inspiring role models.
- I knew that women were not respected in mathematics but it was worse than I imagined.
- I personally enjoy doing math yet as a kid I was told that it is hard for a girl like me to understand and succeed in doing math [27].

Some of these comments made reference to more specific gender issues, such as numbers of female math faculty, support for female students, and ways in which female students are treated in math classes:

Table 21.1 What section, dance, or story stood out the most?

	Female students	Male students
Stories of women mathematicians	11	3
"Hand dance", no reference to gender issues	2	14
Rice's tesselation discoveries	11	5
"Dr. Jones" micro-inequity skit	5	6

- Even now I have seen few female math teachers, something I hope is remedied.
- One thing that I can relate to is that many of the women were not allowed to go to school but still went and became educated individuals and I am the same way because in my culture women are usually not the ones to go to school.
- Sometimes when doing math I do in fact think guys know more just because they always speak up. Also, I've only ever had guy mathematicians. Now that I've seen this performance it's opened my eyes more.
- I can relate the performance to one experience I have had in mathematics. In one of my previous math classes there was a group of students who asked this one girl to basically do their work for them. She was very nice and did what she could and when the group presented they claimed to have done it all on their own without even giving her credit. Watching the performance reminded me of that moment when credit was not given where it was deserved.[6]

A number of the comments indicated that students were responding positively to the integration of mathematics and the arts:

- I've never considered that math is everywhere in the way we move until after the performance.
- I was never shown math in such an artistic and exciting way.
- When I was in elementary school I played hand games like Miss Mary Mack. I never thought that the rhythm of the games was math related.
- I play many different instruments, but I never thought of music in terms of math.

Information from student questionnaires also helped us understand faculty support (or lack thereof) for this performance. For example, in a mathematics department consisting of 19 male and 11 female full time faculty, eight of the faculty had students attend the concert: six of those faculty were female and two males (including myself). The dance department has two full-time male faculty, yet the only students we could identify as attending from dance classes were from the classes of two part-time women dance instructors. A 2012 research study points to issues such as this, noting that "…subtle bias against women was associated with less support for the female student, but was unrelated to reactions to the male student. These results suggest that interventions addressing faculty gender bias might advance the goal of increasing the participation of women in science" [20, p. 16474].

Administrative support for this performance was also present but there were revealing inconsistencies, in some cases involving promised support that was not forthcoming. Funding did, however, come from a number of campus sources: Women's History Events, the student government, a developmental and readiness education committee, the mathematics department, and the De Anza Institute for Community and Civic Engagement. However, it seems clear to us that even in institutions with strong public commitments to the principles of gender equality, serious barriers remain to finding support for performances like this.

[6]This comment was from a male student.

21.9 Plans for the Future

This year we are ramping up marketing for the show and hope to perform it in the next few years in a variety of settings: at schools at all levels from primary grades to college; in theaters; at conferences; and at institutions devoted to science and technology. We plan to continue development of the show, adding material on women of non-European background as well as finding ways to incorporate audience experiences of mathematics. For example, we are looking at incorporating brief stories of two groups of previously unsung women mathematicians and engineers who were central to the planning and execution of early American NASA space shots, as presented in two recent books and a movie: *Rocket Girls* [11] and *Hidden Figures* [29, 30]. Another idea under consideration is to employ instant feedback during the performances via cell phone, as an audience interaction technique. We are also planning to change the title to one that better presents the overall perspective, such as *The Daughters of Hypatia: a Mathematical Herstory*, and also incorporate a now well-known phrase from recent political life, "Nevertheless, she persisted" [4].

A study guide for the performance for use in educational settings is now over 50 pages long and still under development. One primary purpose of the study guide is to help students learn details of the mathematicians' lives and research in greater detail than possible in a short performance. We are also hoping to coordinate performances with more events, such as the display of interactive math puzzles organized by Jim Wilder at one of our performances in Birmingham, AL, and we are considering ways of including contemporary web-based media to present the materials in the study guide online. Those of us involved in the show continue to learn more about the very issues we are presenting as we continue to give performances of it.

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