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MATHEMATICS *in* VICTORIAN BRITAIN

Raymond Flood
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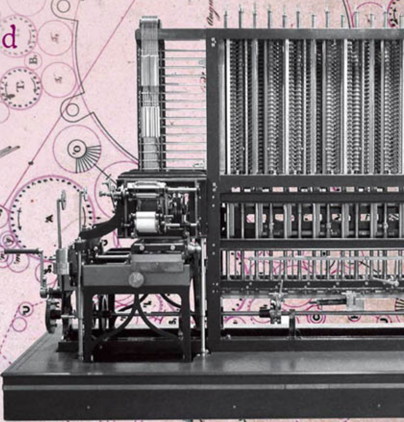

Mathematics in Victorian Britain

Queen Victoria (1819–1901).

MATHEMATICS IN VICTORIAN BRITAIN

Edited by

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and

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FOREWORD

The Industrial Revolution began in the 18th century, and by the time Victoria came to the throne in 1837 Britain led the world in the production of iron, steel, and steam engines. The British navy ruled the world, and the atlas was rapidly being coloured pink as the Empire grew.

This power led to tremendous wealth and tremendous self-confidence. Invention took off: in 1837 about five hundred patents were applied for; by the end of the century there were about two hundred and fifty thousand patent applications every year. Engineers thought they could do anything: they built bridges, railways, and steam-powered machines of every kind.

The electric telegraph started as a warning system to be strung along the newfangled railway lines in order to prevent two trains from using the same single track simultaneously from opposite ends. Within thirty years cables had been laid across the Atlantic Ocean and around the world. From her equipment in Buckingham Palace the queen could in principle send a message to her subjects in a dozen countries and receive a reply within minutes.

Manchester and its outlying towns were built almost entirely on the wealth from the cotton trade—Oldham alone boasted more than three hundred mills—and the amount of money sloshing about was extraordinary. At one point it was claimed that ninety per cent of all the world's cotton passed through the port of Liverpool.

This spirit of enthusiasm and the 'can-do' attitude invaded not only engineering and commerce, but the academic world too. There was more time and support for research. Mathematics was not merely a question of reciting Euclid in order to become a vicar; instead, people began to peel back the intricate petals of the subject, both for its own sake and for practical ends.

The result was a splendid flowering, in areas ranging from algebra and geometry to electromagnetism and mathematical machinery—and this book will take you on a splendid walk through the garden of Victorian mathematics.

Adam Hart-Davis

PREFACE

Today, the history of 19th-century mathematics is a well-studied and vibrant area of research, with books, articles, and scholarly papers published frequently on various aspects of the subject. One of these aspects is the development of mathematics in Victorian Britain, a period of tremendous vitality and change—social, political, and scientific. In recent years, numerous scholars worldwide have undertaken research into facets of the history of Victorian mathematics, resulting in a variety of published works. However, most of this research has appeared in specialized and hard-to-find scholarly journals, practically inaccessible to all but the most devoted historian of mathematics. Moreover, since these publications have largely focused on specific themes or mathematical areas, no single volume has explicitly considered the broad topic of mathematics in Victorian Britain, until now.

This book thus serves two purposes:

- it constitutes what is perhaps the first general survey of the mathematics of the Victorian period;
- it assembles, for the first time in a single source, researches on the history of mathematics in Victorian Britain that would otherwise be out of the reach of the general reader.

The chapters have been contributed by a group of sixteen authors, with topics corresponding to their individual areas of research. Some of this research receives its first publication on these pages; other chapters are based on older work that has appeared elsewhere but is all but unavailable to those without access to research journals or large university libraries. Consequently, the chapters feature a variety of styles and levels of technical difficulty, depending on their area of coverage. Thus, while they no doubt differ in their level of accessibility, we hope that they will nevertheless be found to be interesting and informative.

Whereas some books on the history of mathematics concentrate on the contributions of particular individuals, and while the following pages will feature details of a number of mathematicians and their work, we have chosen a different approach for this volume, focussing on two main themes.

The first of these is geographical, with six chapters detailing mathematical life in London, Oxford, and Cambridge, as well as Scotland, Ireland, and the British Empire. The motivation for this theme is three-fold. First, these chapters chart the growth and institutional development of mathematics as a profession through the course of the 19th century. Second, they document changes in the teaching of the subject at the principal British centres of higher mathematics education. And third, the chapters provide a contextual background for the discussion of the mathematics and mathematicians featured in the second part of the book.

Following a chapter highlighting the dissemination of mathematics in Victorian Britain via journals and learned societies, the second thematic part of the book focuses on developments in specific mathematical areas, with ten chapters ranging from pure mathematics (such as geometry, algebra, and logic) to the applied sciences (including statistics, calculating machines, and astronomy). Finally, lest the reader assume that the mathematical developments in Victorian Britain are beyond criticism, we close with Jeremy Gray's somewhat subversive epilogue, which argues against viewing the contributions of Victorian British mathematicians too indulgently.

Naturally, as the first book of this kind, this volume cannot hope to be comprehensive, and the motivated reader will no doubt find topics that are missing or only minimally discussed. Such topics include school-level mathematics education; engineering, military, or actuarial mathematics; interactions and correspondence with European and American mathematical contemporaries; and larger sociological issues, such as the role of women in Victorian intellectual society. While all of these subjects (and more) were considered for inclusion, we felt that, under the necessary constraints of a volume of manageable scope and size, there was simply not enough room. Indeed, any one of these topics could provide sufficient material for several books of this size. These limitations notwithstanding, we hope that as an overview of recent and ongoing research this book will provide both information and inspiration for future work.

As with many edited volumes, this book is not necessarily intended to be read from cover to cover, although it can be. Rather, it is intended to serve as a valuable resource to a variety of audiences. It is our hope that mathematicians with little or no knowledge about the development of their field will find many of the historical details stimulating and intriguing, and that the specialist historian of mathematics will view its assorted surveys as a useful resource and an impetus towards further research in the area. For the more general reader, we hope that it will provide an introduction to a fascinating and little-known subject that continues to stimulate and inspire the work of scholars today: mathematics in Victorian Britain.

The Editors
June 2011

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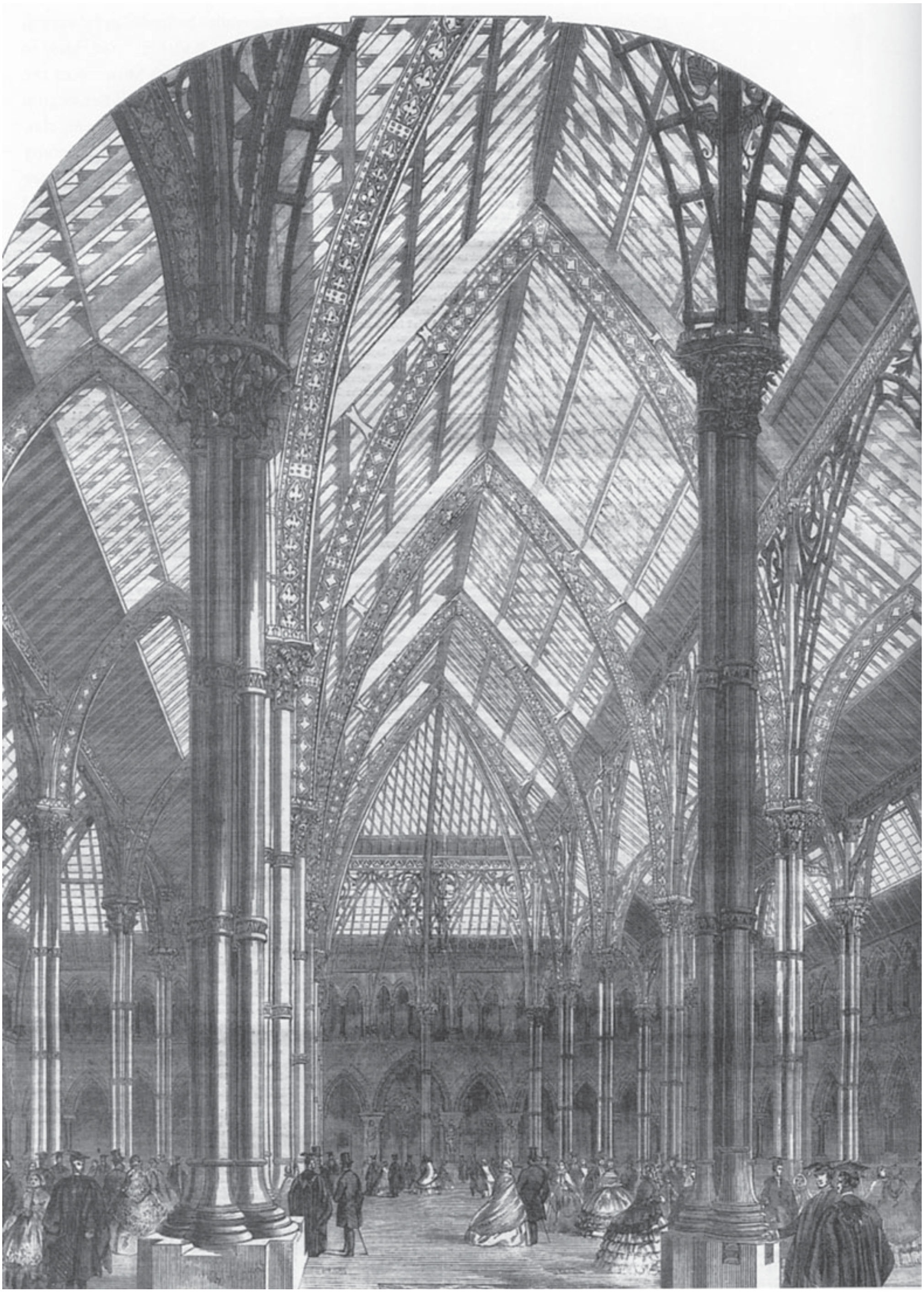


Oxford's neo-gothic University Museum, seen here shortly after its opening in 1860, was specifically designed to improve the provision of mathematics and science in mid-Victorian Oxford.

Introduction

ADRIAN RICE

Although the Victorian era was characterized by the dominance of Great Britain, both militarily and economically, the accomplishments of the British in mathematics seem, at first sight, rather less spectacular. However, significant contributions were made by British mathematicians throughout the period, with vectors, matrices, and histograms being just a few of the mathematical innovations for which they were responsible. In this preliminary survey of some of the achievements of Victorian mathematics, we highlight not just those mathematical scholars such as Charles Babbage, James Clerk Maxwell, and Bertrand Russell who are still well known today, but also draw attention to the lesser known mathematical contributions of other prominent Victorians such as Florence Nightingale and Lewis Carroll.

On 2 November 1839, the British literary magazine the *Athenæum* published an article in which was contained the following, apparently unremarkable, sentence:

> Perhaps the Annean authors, though inferior to the Elizabethans, are, on a general summation of merits, no less superior to the latter-Georgian and Victorian.[1]

The anonymous author of this article thus distinguished his otherwise run-of-the-mill essay by providing the first appearance (in print at least) of a new contribution to the English language: the word *Victorian*.

This word has been used ever since to denote something typical of, or belonging to, the sixty-four-year reign of Queen Victoria, and provides, at least in part, the title of this book. Since the First World War—and, in particular, assaults on the preceding generation by the outspoken writer, critic, and Bloomsbury-group leading light Lytton Strachey—the word 'Victorian' has often been used in a somewhat derogatory manner to mean 'old-fashioned', 'out-dated',

Queen Victoria at the beginning of her reign.

'backward-looking', and 'reactionary', among other things. And, while some of the mathematics practised in Victorian Britain might appear somewhat outmoded today, much also seems recognizably contemporary. Indeed, to the modern-day mathematician, Victorian mathematics is a curious mixture of both the antiquated and progressive!

The Victorian era, which lasted from 1837 to 1901, was the age of Peel and Palmerston, Gladstone and Disraeli, Tennyson and Thackeray, Dickens and Wilde, Stanley and Livingstone, Gilbert and Sullivan. It was the age of the Great Exhibition, the Crimean War, the Suez Canal, the Indian Mutiny, and the American Civil War. It was characterized by rapid industrialization and urban growth, far-reaching social and political reforms, vast colonial expansion overseas, and impressive scientific development: increased urbanization resulted in Britain moving from being a primarily agrarian to a largely industrial society; parliamentary reforms enfranchized whole new sections of the population; innovations such as the telegraph and the railways revolutionized daily life; while Darwin's theory of evolution challenged the very basis of people's beliefs.

Not surprisingly, the Britain of 1837 was very different from the nation that entered the 20th century in 1901. In 1837 there were no telephones, no light bulbs, no motor cars. X-rays and electrons had still to be discovered, as had the planet Neptune. There was no income tax, evolution was not a mainstream scientific theory, and the Pope was still fallible. Slavery was still legal in the southern-most members of the twenty-six United States of America. And, despite being recognized geographical entities, the countries of Italy, Germany, Canada, and Australia had yet to be created as distinct unified sovereign nations. All this would change in the sixty-four years from 1837 to 1901.

The Victorian age is remembered, in the UK at least, as the period when Britain rose from being a major military and economic force to the hub of the most powerful and extensive empire the world had ever seen. It was an age of pride and 'jingoism' (a very Victorian word)—a time when Britain quite literally 'ruled the waves'.

But whereas Britain dominated the 19th century militarily and economically, we have to search harder to uncover its Victorian mathematical heritage. Were we to list the most influential mathematicians who were active during this period (among them Gauss, Cauchy, Jacobi, Riemann, Weierstrass, Cayley, Maxwell, Cantor, Klein, Poincaré, and Hilbert), we would find that the British names are far outnumbered by their French and German counterparts. Indeed, mathematically, this period was characterized by the dominance of the French giving way to the rise, in particular, of German mathematics, with British mathematics being relatively peripheral. Nevertheless, there are still compelling reasons to devote an entire book to the fascinating story of mathematics in Victorian Britain.

After a long period of stagnation from about 1750 to 1830, British mathematics experienced a dramatic renaissance during Queen Victoria's reign, with a resurgence of interest and achievement in the subject. British Victorian mathematicians made numerous significant contributions to mathematics in this period and, as we will see, were innovators in several respects. Indeed, anyone who has

Oxford Circus in London in Victorian times.

studied mathematics at school or university will have come across at least some of the fruits of this remarkably fertile period: matrices, vectors, Maxwell's equations, Boolean algebra, histograms, and even the concept of standard deviation, were all invented by British mathematicians of the Victorian era. To provide a backdrop for the chapters that follow, this introduction highlights just a few of the many mathematical developments made in Britain during this time.

Sixty-four years of invention and discovery

The Victorian period coincided with a revival of British mathematics from its mid-18th-century slump. Despite the strong impetus given to British mathematics by the prestige and achievements of Isaac Newton and the ability of his immediate successors (such as Roger Cotes, Brook Taylor, Colin Maclaurin, and Thomas Simpson), British mathematics had entered a period of stagnation from the middle of the 1700s.[2] Indeed, no really first-rate mathematicians were produced from about 1750 until around 1830.

By that time, Charles Babbage was lamenting what he termed 'the decline of science in England' in the title of a widely-read book. In it he wrote:[3]

> …in England, particularly with respect to the more difficult and abstract sciences, we are much below other nations, not merely of equal rank, but below several even of inferior power.

Quoting fellow mathematician and friend John Herschel, he added:[4]

> In mathematics we have long since drawn the rein, and given over a hopeless race.

The good news was that, by the time these words were published, Britain was emerging from what has been described as 'its mathematical fog'.[5] By the early 1800s, mathematicians at the University of Edinburgh, the University of Cambridge, and Trinity College, Dublin, were initiating an interest in Continental results, a trend furthered by subsequent scholars, including George Peacock, William Whewell, and Babbage and Herschel themselves.

There were several reasons why 18th-century British mathematics had lagged so far behind that of mainland Europe, and these factors remained well into the 19th century. The country's peripheral geographical position, together with the effects of a prolonged war with France, resulted in the slight delay and limited availability of Continental publications reaching its shores. Thus, while still in touch with developments in mainland Europe, mathematicians in Britain were inevitably slower in assimilating results from the continent than might otherwise have been the case. The most obvious example was their patriotic insistence on sticking to (and failing to develop adequately) Newton's fluxional version of the calculus in the face of more versatile Continental equivalents.[6]

Another was the famous distrust of complex numbers, imaginary quantities, and even negative numbers, by several high-ranking British scholars.[7] For a variety of mathematical and philosophical reasons, the meaning, interpretation, and legitimacy of negative (and, by extension, imaginary and complex) numbers were called into question. The most vocal opponents of the use of such 'impossible' quantities were the Cambridge-trained mathematicians Francis Maseres and William Frend, who in various publications argued vigorously for their rejection, stimulating a fierce debate on the veracity of their use in mathematics. Consequently, the last half of the 18th century and the opening third of the 19th saw the question of negative and imaginary numbers occupy a major place in the discussions of British mathematicians, philosophers, and men of science.[8]

George Peacock (1791–1858).

Indeed, as the Victorian era began, British algebraists were only just beginning to move on. In his *Treatise on Algebra* of 1830 and his book-length 'Report on the recent progress and present state of certain branches of analysis' of 1833, George Peacock had initiated a different, and more abstract, algebraic methodology that fundamentally altered the way the subject was perceived in Britain. His emphasis was not on what negatives and imaginaries actually meant, but rather on the laws under which they operated. Thus, for Peacock, algebra was a subject based not on generalizations of arithmetical concepts, but on a series of formal assumptions or axioms. In short, in order to legitimize the use of negative and imaginary quantities in algebra, Peacock had answered, not by attempting to clarify the meaning of such entities, but by redefining what was meant by algebra itself.[9]

Among those following Peacock's more axiomatic approach to algebra was the Cambridge-educated Scottish mathematician Duncan Gregory. Having been heavily influenced by his reading of recent French mathematics, he published the first explicit mention of the commutative and distributive laws in an English work in 1838.[10] The commutative law, which for addition may be stated as

$$a + b = b + a,$$

and the distributive law,

$$a(b + c) = ab + ac,$$

are simple rules from everyday arithmetic, which at that time were believed to be universal truths in algebra too. Indeed, to those today who have studied algebra only at school, the idea that these rules may not always hold may still seem vaguely unnerving! However, by arguing that such laws 'may be said to exist by convention only',[11] Peacock and Gregory questioned this universality for the first time, raising the possibility of constructing new algebras that are independent of the usual rules of arithmetic.

The first such algebra was created by the Irish mathematician, Sir William Rowan Hamilton in 1843: his creation (or discovery) of quaternions was rightly regarded as ground-breaking. Here, for the first time, was an algebraic system in which, although $a + b$ is the same as $b + a$, the quantity $a \times b$ does not necessarily equal $b \times a$. It was thus the first fully consistent algebraic system to break one of the previously inviolable laws of arithmetic: commutativity.

It also enlarged the world's mathematical vocabulary: the terms *quaternion*, *scalar*, and *vector* (in its modern sense) were all coined by Hamilton in 1843. Whereas normal complex numbers, $a + bi$, were composed of a real and imaginary part, quaternions were four-part complex numbers of the form

$$a + bi + cj + dk,$$

where a is the real, or 'scalar', quantity and the i, j, and k components form the imaginary part. Hamilton called this latter quantity the 'vector' part, with the three constituents representing three perpendicular lines; this explains why, to this day, when studying vectors in three dimensions we label their components i, j, and k. Hamilton and his like-minded mathematical followers worked vigorously to apply quaternions to geometrical and physical problems; indeed, when James Clerk Maxwell published his revolutionary *Treatise on Electricity and Magnetism* in 1873, the now-famous 'Maxwell's equations' were stated there in terms of quaternions. But it was not long before they received their current form as vector equations. Thus, a consequence of Hamilton's quaternions was the development throughout the Victorian era (mainly by British applied mathematicians) of the algebra and calculus of vectors, essential to modern-day mathematical physics.[12]

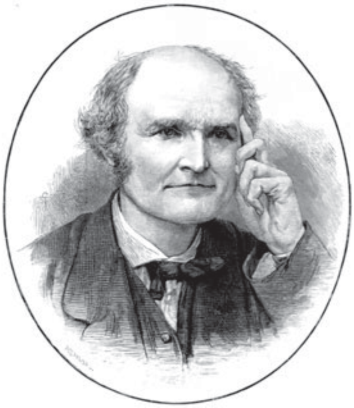
William Rowan Hamilton (1805–65).

With the law of commutativity breached, it was not long before other algebras were developed, and once again British mathematicians were in the vanguard. Within months of Hamilton's discovery of quaternions, his friend John Graves and the Englishman Arthur Cayley had independently created a consistent algebra of complex numbers with eight components, one real and seven imaginary, called *octonions*. These numbers turned out to be even more unusual because, in addition to violating the commutative law of multiplication, they also break the associative law: for octonions, we have

$$(a \times b) \times c \neq a \times (b \times c).$$

In 1878 this idea was generalized still further by William Kingdon Clifford to comprise systems with 2^n components, an area now known as *Clifford algebras*.[13]

Another very different form of algebra invented in Victorian Britain, and one with which many are familiar today, is that of *matrices*. The term 'matrix' had first been given in 1850 in an article by James Joseph Sylvester. But in 1858, in a landmark paper, Cayley used this definition as the basis of a brand new area of mathematics: the algebra of matrices.[14] Cayley quickly found that, just like quaternions, matrices do not always give the same results when multiplied together in different orders: matrix multiplication is also non-commutative. Over the next quarter-century, Cayley and Sylvester, together with other British mathematicians such as the Oxford professor Henry Smith, developed this new mathematical subject, helping to lay the foundations for much of what we today call *linear algebra*.



Arthur Cayley (1821–95).

Cayley and Sylvester were also largely responsible for the creation of a totally new area of algebra, which quickly became almost an obsession for several British Victorian mathematicians. The subject of *invariant theory* involved, among other things, the search for algebraic expressions known as *invariants* (a word coined by Sylvester in 1851), whose basic form is preserved when they undergo a particular kind of transformation. These searches became increasingly complicated and time-consuming as higher-degree expressions were investigated. This time, although the British could be considered the originators of the theory, it was the Germans who produced the deeper results. Their more theoretical and abstract approach contrasted sharply with the British reliance on computation.[15]

Indeed, Victorian British mathematics was often characterized by a far greater concern for computational techniques and mastery of symbolic manipulation, than for rigorous proof. For example, in his inaugural paper on matrices of 1858, Cayley proved a fundamental result (now known as the *Cayley–Hamilton theorem*) for 2×2 matrices, noting that he had verified it for the 3×3 case, but saying that:[16]

> I have not thought it necessary to undertake the labour of formal proof of the theorem in the general case of a matrix of any degree.

Statements like this, and others such as 'similar proofs may be given for equations of higher degree', occur regularly in British work of this time.

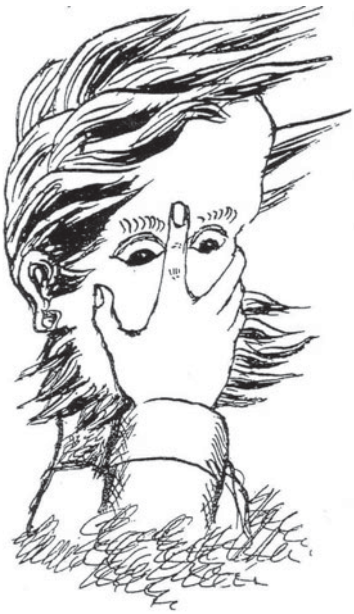
Meanwhile, at Oxford in the mid-1860s, a mathematics lecturer by the name of Charles Dodgson was researching an area very closely related to matrices, that of determinants. A *determinant* is a particular number or expression related to a matrix, from which important algebraic and geometrical characteristics can be deduced. For 2×2 matrices, determinants are very easy to find, but things quickly get more complicated, and by the time one gets to 5×5 matrices, the computations are very laborious indeed. But Dodgson created an ingenious method that only ever required the calculation of 2×2 determinants; this was a considerable achievement, especially considering that, at roughly the same time

James Joseph Sylvester (1814–97).

under his pen-name Lewis Carroll, he had completed his first children's book, *Alice's Adventures in Wonderland*.[17]

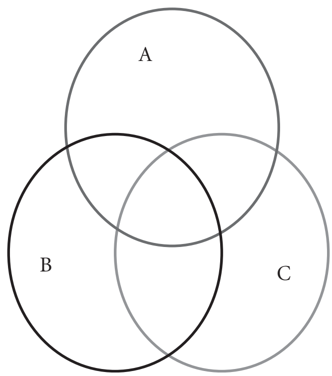
Another area in which Dodgson worked was logic. Although logic was a subject with a long and varied history, it was a relative newcomer as a mathematical discipline. In fact, at the beginning of our period it was not even considered a part of mathematics at all: to study logic was to study a branch of philosophy. But it was not long before a disciplinary shift began. In 1839, stimulated by its use in teaching geometry from Euclid's *Elements*, the mathematician Augustus De Morgan began researching into the study of logic as a means of facilitating geometrical proof. This led him into full-blown publications in the 1840s, in which he developed a symbolic notation for making logical deductions. Unfortunately for De Morgan, this work on logic resulted in his being drawn into a dispute with the Scottish philosopher Sir William Hamilton, a firm believer in preserving the disciplinary boundaries between logic and mathematics.[18]

In 1847, Hamilton erroneously accused De Morgan of plagiarizing his ideas on quantification of the predicate, since both men had been working on (very different) modifications to quantified logical statements, such as 'all men are mortal' and 'no dogs are cats'. This charge turned out to be unfounded, but De Morgan's work marked the birth of algebraic logic, wherein logical premises are manipulated purely symbolically in order to derive consequent conclusions. A further consequence of this lengthy battle with Hamilton was that it prompted De Morgan's friend, the Lincoln-based mathematician George Boole, to enter the subject, resulting in the creation of what was to become *Boolean algebra*.[19]



A self-portrait by the Revd. Charles Dodgson: 'what I look like when lecturing'.

Among those to take up the new algebraic approach to logic was the Cambridge academic John Venn in the 1880s. Venn's current fame rests principally on his introduction in 1880 of diagrammatic representations of logical relationships, his so-called *Venn diagrams*. Actually, the pictures we now refer to as 'Venn diagrams' might more accurately be called 'Euler circles', since they were first popularized by the Swiss mathematician Leonhard Euler in his *Letters to a German Princess* (1768), and even these first occurred in the work of Leibniz.[20] But Venn did something different: first he generalized Euler's system considerably, and secondly he based his logical diagrams firmly on the algebraic traditions initiated by De Morgan and Boole a generation before. He thus established a powerful and general method by means of which logical problems can be solved purely symbolically.[21]



A 'Venn diagram' with three circles.

Through the work of Venn and others, including Charles Dodgson, symbolic logic continued to develop and thrive until, by 1900, it had attracted the attention of perhaps its most famous British practitioner, Bertrand Russell. However, in contrast to preceding British logicians, the influences on Russell came almost exclusively from overseas—in particular the work of Georg Cantor and especially Giuseppe Peano and Gottlob Frege. Moreover, whereas Boole, De Morgan, and other algebraic logicians had based their logic on mathematics, Russell and his fellow logicists were trying to show that mathematics could be grounded on logic.[22] The culmination of their efforts came in the publication of Russell's monumental

86 CARDINAL ARITHMETIC [PART III

***110·632.** $\vdash : \mu \in \mathrm{NC} \,.\, \supset \,.\, \mu +_c 1 = \hat{\xi}\{(\exists y) \,.\, y \in \xi \,.\, \xi - \iota' y \in \mathrm{sm}``\mu\}$

Dem.

$\vdash \,.\, *110{\cdot}631 \,.\, *51{\cdot}211{\cdot}22 \,.\, \supset$

$\vdash : \mathrm{Hp} \,.\, \supset \,.\, \mu +_c 1 = \hat{\xi}\{(\exists \gamma, y) \,.\, \gamma \in \mathrm{sm}``\mu \,.\, y \in \xi \,.\, \gamma = \xi - \iota' y\}$

$[*13{\cdot}195] \quad = \hat{\xi}\{(\exists y) \,.\, y \in \xi \,.\, \xi - \iota' y \in \mathrm{sm}``\mu\} : \supset \vdash \,.\, \mathrm{Prop}$

***110·64.** $\vdash \,.\, 0 +_c 0 = 0$ [*110·62]

***110·641.** $\vdash \,.\, 1 +_c 0 = 0 +_c 1 = 1$ [*110·51·61 . *101·2]

***110·642.** $\vdash \,.\, 2 +_c 0 = 0 +_c 2 = 2$ [*110·51·61 . *101·31]

***110·643.** $\vdash \,.\, 1 +_c 1 = 2$

Dem.

$\vdash \,.\, *110{\cdot}632 \,.\, *101{\cdot}21{\cdot}28 \,.\, \supset$

$\vdash \,.\, 1 +_c 1 = \hat{\xi}\{(\exists y) \,.\, y \in \xi \,.\, \xi - \iota' y \in 1\}$

$[*54{\cdot}3] \quad = 2 \,.\, \supset \vdash \,.\, \mathrm{Prop}$

The above proposition is occasionally useful. It is used at least three times, in *113·66 and *120·123·472.

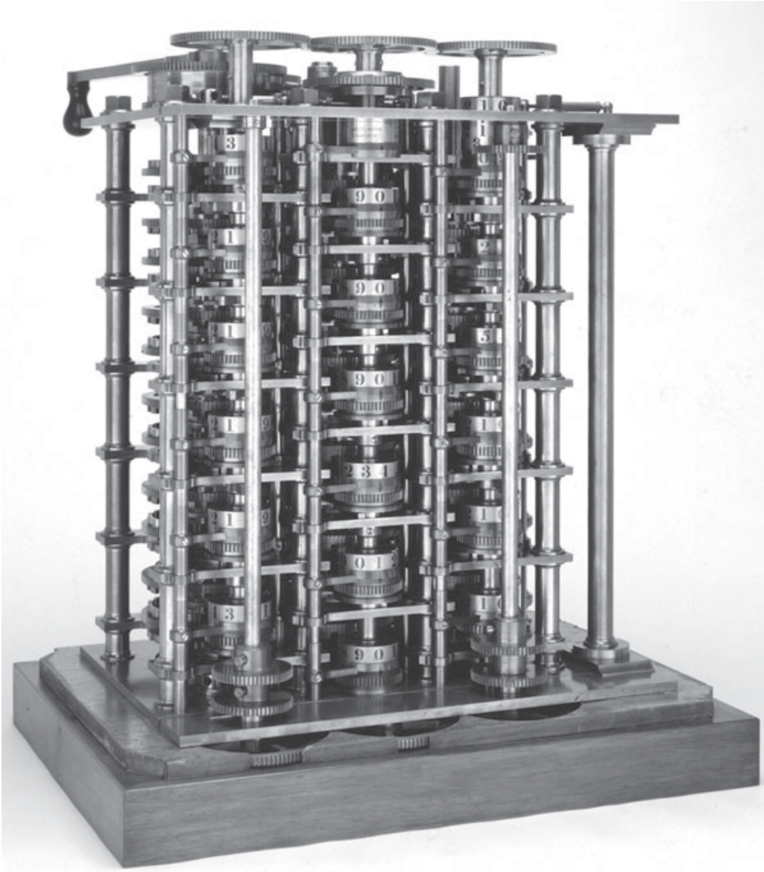
Russell and Whitehead's proof that 1 + 1 = 2.

three-volume collaboration with his former Cambridge tutor Alfred North Whitehead, *Principia Mathematica* (1910–13), which today is perhaps most famous for taking several hundred pages to build up to a proof that 1 + 1 = 2—a result that they described as being 'occasionally useful'![23]

Of course, the most well known application today of symbolic logic is computing, and one of the forefathers of today's programmable computer was that most famous of Victorian technological pioneers, Charles Babbage. He is often remembered for designing precursors to the modern computer that were never built.[24] The first, his Difference Engine no. 1, was designed in the 1820s, but it was his analytical engine of the 1830s that was particularly remarkable. Designed as a more general-purpose calculating machine, it also featured aspects of data storage and programmability.[25]

Augusta Ada King (Countess of Lovelace) (1815–52).

This feature was famously explored by Ada King, Countess of Lovelace, the only legitimate child of Lord Byron, and a long-time friend of Babbage. Gifted with an ability and intense interest in science and mathematics, she had been tutored privately by a number of family friends, including William Frend and Augustus De Morgan. In 1843, in a series of commentaries on Babbage's machine, she gave a table of execution for an algorithm that Babbage wrote to calculate the series of coefficients known as the Bernoulli numbers.[26] For this reason, she is often credited with being the world's first computer programmer, and it was in her honour that the programming language Ada was so named in 1979.



Babbage's Difference Engine No. 1, demonstration assembly, 1832.

Naturally, due to Babbage's failure to see any of his projects to completion, his and Lovelace's achievements in this area of applied mathematics can only be appreciated in retrospect. But quite the opposite is true of many other areas of mathematical applications. Indeed, if there was one area of Victorian mathematics of which the British could be uniformly proud, it was mathematical physics.

William Thomson—a sketch at age 16 by his sister Elizabeth.

In this field the Scotsman William Thomson—better known today as Lord Kelvin—acquired a high reputation, both at home and overseas, while still fresh out of Cambridge. Well known and respected abroad, he published widely in many areas of applied mathematics. His work on thermodynamics led him to propose the well-known absolute scale of temperature in 1848, and his *Treatise on Natural Philosophy*, co-authored with P. G. Tait, was one of the most influential textbooks on physics of the entire Victorian era.[27] Most significantly, with respect to furthering the work of British mathematicians, he famously promoted the hitherto obscure *Essay on the Application of Mathematical Analysis to Electricity and Magnetism* by the recently deceased George Green.[28]

Green's windmill in Sneinton, Nottinghamshire.

Green had spent most of his life working in the family mill just outside Nottingham.[29] A self-taught mathematician, he published his *Essay* at his own expense in 1828. The work was remarkable—introducing the concept of *potential*, as now used in physics, and containing an important result now known as *Green's theorem*—but initially went unnoticed by the mathematical community at large. Nevertheless, Green was encouraged to develop his scientific credentials, and in 1833 he entered Cambridge as a mature student, graduating in 1837, and continued to publish papers on mathematical physics. Sadly, his health deteriorated and he died in 1841 at the age of just 47. But his mathematics was rescued from obscurity by Thomson; indeed, the fact that we call his key result *Green's theorem* is due to Thomson's tireless promotion of the *Essay*, particularly in France, where papers arising from it appeared in *Liouville's Journal* in the 1840s, and Germany, where Thomson arranged for the whole work to be reprinted with an introduction in *Crelle's Journal* in the 1850s.[30]

Thomson was also responsible for an important generalization of Green's theorem, which first appeared in a letter from him to fellow applied mathematician George Stokes on 2 July 1850. Three and a half years later, in January 1854, Stokes set the result (now named after him) as a question in a Cambridge University prize exam paper.[31] The student who won the prize that year was a certain James Clerk Maxwell, so we may infer that he was presumably one of the first to prove Stokes' theorem! This result later appeared in the opening chapter of Maxwell's ground-breaking *Treatise on Electricity and Magnetism*, which revolutionized the subject and featured the first appearance of Maxwell's equations (albeit in a much more involved quaternion form, as mentioned above).

James Clerk Maxwell (1831–79).

8. If X, Y, Z be functions of the rectangular co-ordinates x, y, z, dS an element of any limited surface, l, m, n the cosines of the inclinations of the normal at dS to the axes, ds an element of the bounding line, shew that

$$\iint\left\{l\left(\frac{dZ}{dy}-\frac{dY}{dz}\right)+m\left(\frac{dX}{dz}-\frac{dZ}{dx}\right)+n\left(\frac{dY}{dx}-\frac{dX}{dy}\right)\right\}dS$$
$$=\int\left(X\frac{dx}{ds}+Y\frac{dy}{ds}+Z\frac{dz}{ds}\right)ds,$$

the differential coefficients of X, Y, Z being partial, and the single integral being taken all round the perimeter of the surface.

9. Explain the geometrical relation between the curves, referred to the rectangular co-ordinates x, y, z, whose differential equations are

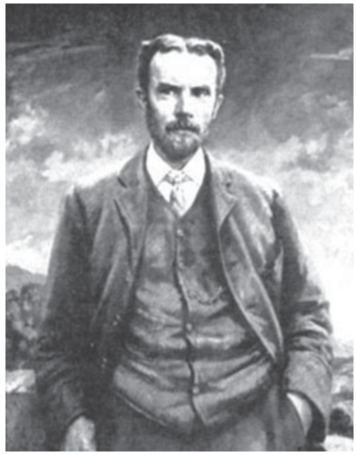
$$\frac{dx}{P}=\frac{dy}{Q}=\frac{dz}{R},$$

and the family of surfaces represented by the partial differential equation

$$P\frac{dz}{dx}+Q\frac{dz}{dy}=R.$$

Stokes's theorem: Question 8 in the 1854 Smith's prize examination paper.

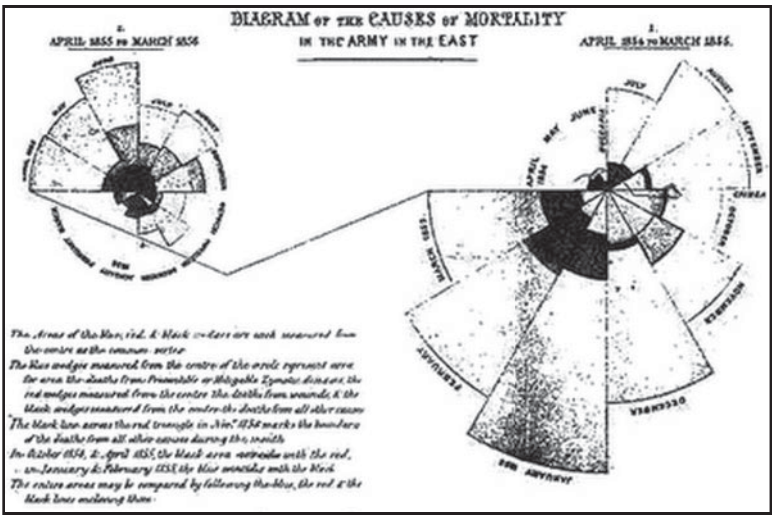
These twenty equations were later simplified down to four in their vector form, by Oliver Heaviside in the 1880s.[32]



Oliver Heaviside (1850–1925).

Among several other significant British Victorian contributors to mathematical physics, we mention John Strutt, the 3rd Lord Rayleigh, who contributed to wave theory, acoustics, and the theory of gases. Horace Lamb made important contributions to fluid dynamics, and Joseph Larmor worked on electricity, dynamics, and thermodynamics, being instrumental in restructuring the subject of electromagnetism around the theory of the electron. The first physicist to use what are now known as 'Lorentz transformations', Larmor's research was backed up by J. J. Thomson's experimental identification of the electron in 1897.[33] Valuable contributions by applied mathematicians such as these and others made mathematical physics the indisputable forte of British Victorian mathematics.

But the Victorians did not just apply mathematics to physics. Mathematical methods were also introduced into a variety of areas in the social sciences, medicine, and public health. One of the leaders in this field was one of the most famous of all Victorians, Florence Nightingale. Although best remembered as a humanitarian and founder of the modern nursing profession, Nightingale also pioneered the introduction of statistical methods into medicine, following her studies of the effects of disease on soldiers in the Crimean War published in 1858.[34] In this work, she popularized the then novel use of diagrams to represent statistical information, particularly by means of her *polar area graph*, similar to the modern pie chart. Her graphical representations were among the first visual presentations of statistics to be accessible to the general reader, and highlighted the extent of the unnecessary deaths during the war most effectively. Moreover, their user-friendly format served as an effective tool to persuade parliament and the medical profession of the advisability of sanitation reforms.



Florence Nightingale's polar area graph.

Karl Pearson (1857–1936).

Many of Nightingale's ideas were championed by Francis Galton, who also tried to mathematize Darwin's theory of evolution by looking at the inheritance of variation,[35] originating the statistical study of regression. The related correlation coefficient was defined soon afterwards by Karl Pearson, who studied how to analyse relationships between several variables.[36] Pearson introduced several now-commonplace statistical tools. One of these was the *histogram*, a diagram similar to a bar chart, but which represents a set of continuous, rather than discrete, data. For this reason, Pearson explained that it could be employed as a tool in the study of history, for example to chart historical time periods, and coined the name 'histogram' in 1891 to convey its use as a 'historical diagram'. In the following year, he devised a sophisticated new statistical function to measure the spread of data sets around their mean. This function, which he called the *standard deviation*, is now a fundamental concept in mathematical statistics. One of Pearson's most celebrated contributions to the subject came at the very end of the Victorian period. His *chi-square test* for goodness of fit between observed data and values predicted from a hypothesis was published in 1900. It is now a standard and widely used method in modern statistics.[37]

For over fifty years from 1884, Pearson worked at University College London, initially as its professor of applied mathematics. But in 1911, he founded a new department of applied statistics—the first of its kind in Britain. It was there that Pearson, and the school of students that grew up around him, went on to lay the groundwork that was in many ways responsible for the creation and establishment of the theory of statistics as a mathematical discipline in the early decades of the 20th century.[38]

Conclusion

This overview gives just a flavour of the many contributions made by British mathematicians between 1837 and 1901. Of course, it is by no means exhaustive: we could go on to mention British contributions to further areas, such as graph theory, combinatorics, mathematical economics, and astronomy, to name but a few, but in view of the many mathematical developments that took place in Victorian Britain, one should not be tempted into a Whiggish historical perspective of 'onwards and upwards'. Indeed, when studying the mathematics of the Victorian era, we should be aware of certain peculiarities and differences that distinguished British mathematical practice from that elsewhere, particularly in mainland Europe.

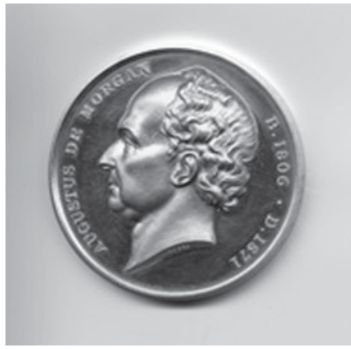
The first concerns the lack of a genuine research ethos at British Victorian universities. This contrasts considerably with the situation in Germany, where mentors such as Klein in Göttingen and Weierstrass in Berlin actively created an environment to encourage their students to emulate their research interests. Compare this with Britain, where the leading mathematicians at this time were solitary figures who did little to lead students into research. Among students and lecturers alike, original research was never an explicit requirement, or even an implicit expectation, at Cambridge or anywhere else in Victorian academia. A true research ethos came into being in British universities only around the First World War.

That said, Britain was essentially the first to establish what became a national learned society devoted purely to research in mathematics.[39] Founded in 1865, the London Mathematical Society (LMS) quickly developed from a local body to the *de facto* national society for British mathematicians.[40] The fact that France followed suit from Britain eight years later was seen by some French savants (such as the geometer Michel Chasles) as further evidence of the decline in their mathematical fortunes.[41] But the LMS also provided a role model for up-and-coming mathematical nations, such as the United States, where the New York Mathematical Society was founded in emulation of its British precursor in 1888, evolving six years later into the American Mathematical Society.[42] But Britain did not just lead the way for emerging mathematical powers in this regard: even Germany—perhaps the world's leading mathematical nation by the end of the 19th century—had no national mathematical society until 1890.[43]

A second difference concerns the range of mathematical subjects studied by the British at this time. Although the interests of Victorian British mathematicians were less specialized than today, there were very few 'universal mathematicians' in the sense of a Gauss, Cauchy, Riemann, Weierstrass, or Poincaré. Although this is due in part to the massive expansion of the subject during this time period, some people, like William Rowan Hamilton and William Kingdon Clifford, were equally comfortable in both pure and applied mathematics. But Cayley was probably the only true British mathematics 'all-rounder' of the period.

Even then there were several areas of the subject missing or largely absent from British mathematics. For example, despite major British contributions to mathematical statistics, there was little original work in probability. Few Victorian British mathematicians were interested in group theory, with one of its (few) practitioners noting that the subject had 'failed, so far, to arouse the interest of any but a very small number of English mathematicians'.[44] There was also very little number theory. However, Henry Smith's monumental *Report on the Theory of Numbers* from the 1860s was highly regarded by European mathematicians—so much so that three decades later, when David Hilbert and Hermann Minkowski were asked to prepare a similar report for the German Mathematical Society, one of the reasons Minkowski gave for his failure to produce his half was the comprehensiveness of Smith's *Report*.[45]

There was also little in the way of analysis (real or complex)—this is ironic, since this area is now such a staple of British university mathematics courses. The change came with the publication of Andrew Forsyth's *Theory of Functions of a Complex Variable* in 1893, which, according to his former student E. T. Whittaker, 'had a greater influence on British mathematics than any work since Newton's *Principia*'.[46] However, the book was not highly regarded outside Britain and in the opening years of the 20th century its standard of rigour was quickly surpassed by younger up-and-coming British mathematicians, particularly Whittaker, W. H. Young, and (most famously) G. H. Hardy and J. E. Littlewood. Together with the reform of the Cambridge mathematics syllabus



The London Mathematical Society's De Morgan medal.

Queen Victoria at the end of her reign.

and its exam system in 1909, these works marked a turning point in the way that pure mathematics was taught and researched in Britain: from then on, analysis would be a fundamental component.

But the very absence of certain mathematical areas gives an indication of the distinctiveness of British mathematics at this time, for its character and style were very different from those of its Continental counterparts. Indeed, there were periods when the mathematical work that was being done was virtually unique to Britain. Consider, for example, the creation of algebraic logic during the 1840s and 1850s: virtually the only people involved (or interested) in this area at that time were George Boole and Augustus De Morgan.[47] Consider also the development of vector algebra in the 19th century: with the principal exceptions of Hermann Grassmann in Germany and Josiah Willard Gibbs in America, a substantial proportion of this work was carried out by British mathematicians.[48] Similarly in the last decades of the period, while scholars such as Galton and Pearson were laying the foundations of modern mathematical statistics, the only comparable work that was happening elsewhere was around Chebyshev in St. Petersburg.[49] Thus, while aware of mathematics from overseas, the British retained their own characteristic style and individualism.

By 1901, British mathematics was certainly less insular than it had been in 1837, but it still had some way to go before becoming fully international. Even though work by British mathematicians was known and appreciated abroad, there were some surprising exceptions. For example, the French organizers of the 1882 prize competition of the Académie des Sciences were embarrassed to learn that the solution to the problem they set had actually been published in Britain by Henry Smith fifteen years earlier, resulting in prizes eventually being awarded to Smith and the young Hermann Minkowski. Interestingly, when Hilbert was preparing his famous address on open mathematical problems for the Second International Congress of Mathematicians (ICM) in Paris in 1900, Minkowski advised him to consult Henry Smith's valedictory presidential address to the London Mathematical Society in which Smith had set out a similar list of topics that he felt warranted further study.[50]

Indeed, the history of the early International Congresses shows how relatively quickly British mathematicians began to participate at the international level after 1900. At the first International Congress of Mathematicians, held in Zürich in 1897, only three British delegates attended and none presented papers. Yet in 1912, just over a decade after the close of the Victorian era, the fifth International Congress of Mathematicians was held at Cambridge, perhaps the surest sign of the growing maturity of British mathematicians in the international arena. As the Oxford algebraist Edwin Elliott observed:[51]

> There was a time not long ago when British Mathematicians may have been thought too self-centred. If the judgment were ever correct, it is no longer. We are alive to what is being done elsewhere, and now aim at cooperation.

In fact, the Victorian age ended just as another renaissance of British (pure) mathematics was on the horizon. The real coming of age of British mathematics happened around the time of the First World War. These were the years that saw the reform of the mathematical syllabus at Cambridge, the foundation of the country's first statistics department by Pearson at University College London, the publication of Russell and Whitehead's *Principia Mathematica*, the beginning of the Hardy–Littlewood collaboration, and the ICM meeting at Cambridge. These events would have profound and long-lasting consequences for the future of British mathematics. But they did not come from nowhere: the foundations for all of them were laid in the Victorian period. The chapters that follow will focus in greater detail on some of these developments and the environments that produced them.

The Hall at Trinity College, Cambridge, 1838.

CHAPTER 1

Cambridge

The rise and fall of the mathematical tripos

TONY CRILLY

When Queen Victoria came to the throne in 1837, virtually all Cambridge students were obliged to receive a mathematically based education. The students who studied the famed honours degree, the mathematical tripos, faced a challenging course. Even the ordinary degree students received a basic training in the subject, as mathematics was viewed as the key to all further study. During the century, the educational fare at Cambridge became more diverse and later students were freed from this obligation. The traditions of the mathematical tripos came under increasing scrutiny, and by 1901 it was on the brink of a major reform that would leave it barely recognizable from its former self.

On 20 June 1837 King William IV died and the young Victoria became Queen. As a war leader the Duke of Wellington was still a living hero, but the Battle of Waterloo was becoming a historical artefact. It was now permissible to make contact with the mainland of Europe without being admonished for consorting with the enemy.

At home, industrialization gathered pace. In the same year that Victoria began her long reign, Charles Wheatstone and William Cooke took out patents on their electric telegraph, and Isambard Kingdom Brunel's steam-driven *Great Western* crossed the Atlantic in fifteen days. The Great Western Railway's first passengers left Paddington for Bristol Temple Meads, and 'God's Wonderful Railway', the great GWR, joined the capital of the West Country to the London metropolis. Although provincial Bristol was eleven minutes behind London, the railway moved the clocks into line. Cambridge managed to remain isolated for a little longer, but

View of Cambridge from Castle Hill, 1841.

The Market Place in early Victorian Cambridge.

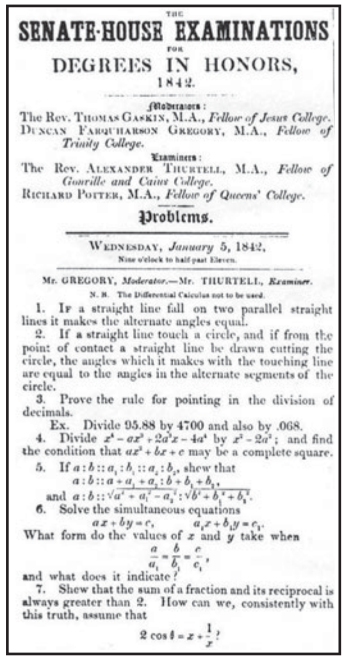
after a town-and-gown debate of some length, the railways came to Cambridge in 1845.

At the beginning of the Victorian period, the market town of Cambridge with its ancient university was the most important place for mathematics in the entire country—the 'holy city of mathematics'. There were two reasons for this. Cambridge University housed the famed mathematical tripos as the mainstream course of study for its students. This was the jewel in the University's crown, and in a religion-dominated society it was likened by many to the Ark of the Covenant. Alongside this venerated institution a new generation of mathematicians was learning to do mathematical research and transmit its work internationally. Indeed, the position of Cambridge as the embryonic national centre for mathematical research was the second reason that placed Cambridge at the fulcrum of mathematics in Victorian Britain.

Old Cambridge reforming: the 1840s

Since the Reformation, one of the principal functions of Cambridge University had been to fill out the ranks of the Anglican Church. But by the 1840s, the choices of future career for its graduates had widened. If students discovered that the Church was not for them, they could become lawyers, schoolmasters, engineers, or men of business. Mathematics had already assumed a central place in the curriculum when the mathematical tripos was instituted in the middle of the 18th century. The mathematics of the tripos was held to be the basis of all study, and it was widely believed that it would hold a man in good stead whatever his future calling. It is a sobering thought that a large proportion of the clergymen, lawyers, and schoolmasters of Victorian England were well grounded in mathematics. Women did not feature in these plans, coming onto the Cambridge scene only in the 1880s.

At the beginning of the Victorian period, the examination for the mathematical tripos was still *the* 'Senate House examination'.[1] Mathematics at Cambridge was regarded as the basis for a 'liberal education'. It was a sort of pre-knowledge and it was held to be important to teach it to the young. Taught too late and it would be as useless as trying to teach 'the violin to a grown man'. The knowledge of mathematics was not claimed to be useful in itself (except for those destined to become tutors or schoolteachers), but it was believed that the study of mathematics would develop and strengthen the faculties of the mind, and *after* the completion of this study one could go on to other fields and be more effective in them. In short, mathematics gave the 'art of acquiring all arts', and like physical games that prepared the body, mathematics toned the intellectual muscle.


THE

SENATE-HOUSE EXAMINATIONS

FOR

DEGREES IN HONORS,

1842.

Moderators:

The Rev. THOMAS GASKIN, M.A., *Fellow of Jesus College.*
DUNCAN FARQUHARSON GREGORY, M.A., *Fellow of Trinity College.*

Examiners:

The Rev. ALEXANDER THURTELL, M.A., *Fellow of Gonville and Caius College.*
RICHARD POTTER, M.A., *Fellow of Queens' College.*

Problems.

WEDNESDAY, *January* 5, 1842,
Nine o'clock to half-past Eleven.

Mr. GREGORY, *Moderator.*—Mr. THURTELL, *Examiner.*

N. B. The Differential Calculus not to be used.

1. If a straight line fall on two parallel straight lines it makes the alternate angles equal.

2. If a straight line touch a circle, and if from the point of contact a straight line be drawn cutting the circle, the angles which it makes with the touching line are equal to the angles in the alternate segments of the circle.

3. Prove the rule for pointing in the division of decimals.

Ex. Divide 95.88 by 4700 and also by .068.

4. Divide $x^4 - ax^3 + 2a^3x - 4a^4$ by $x^2 - 2a^2$; and find the condition that $ax^2 + bx + c$ may be a complete square.

5. If $a : b :: a_1 : b_1 :: a_2 : b_2$, shew that
$$a : b :: a + a_1 + a_2 : b + b_1 + b_2,$$
and $a : b :: \sqrt{a^2 + a_1^2 - a_2^2} : \sqrt{b^2 + b_1^2 + b_2^2}$.

6. Solve the simultaneous equations
$$ax + by = c, \qquad a_1x + b_1y = c_1.$$
What form do the values of x and y take when
$$\frac{a}{a_1} = \frac{b}{b_1} = \frac{c}{c_1},$$
and what does it indicate?

7. Shew that the sum of a fraction and its reciprocal is always greater than 2. How can we, consistently with this truth, assume that
$$2\cos\theta = x + \frac{1}{x}?$$

Senate House examination paper, 1842.

This mathematics-based liberal education was aimed at the middle and upper classes, and for some it was a bitter pill to swallow. But swallow it they must, for students of the 1840s were required to acquit themselves in the mathematical tripos before sitting the examinations for the classics degree, a newcomer course of study established only in 1824. Many a fine classicist was stymied by this requirement; for example, three out of four Kennedy brothers starred as the 'senior classic' (the first in the entire class of classics students), but W. J. Kennedy (the youngest brother) was 'gulfed' in the mathematical tripos examination and so debarred from competing for the classics degree. There were few exceptions to this rule, but in an unreformed Cambridge noblemen were exempted by virtue of their aristocratic birth.

While generations of students passed through the Cambridge system, the mathematical tripos and its examination evolved over the course of Victoria's reign. The tripos examination sat by Arthur Cayley in the 1840s was not the tripos sat by James Clerk Maxwell in the 1850s. This in turn differed from the one sat by

Karl Pearson in the 1870s, and still more from that of Bertrand Russell in the 1890s which was barely recognizable as the same exam of half-a-century earlier. In the 1840s the mathematical tripos was a wide-ranging course covering most aspects of mathematics in some depth, but by the time Russell sat down in the Senate House in 1894 it had become specialized, and the products of the tripos at that time were constricted by a knowledge in a branch of the subject that was acquired towards the end of their studies.

Some institutional practices were central to the mathematical tripos, and though they were vigorously debated at various times they were resistant to change. In this category were:

- The once-and-for-all nature of the mathematical tripos final examination.
- The order of merit—the listing of students according to their marks obtained in the final examination; this was divided into three distinct classes: wranglers, senior optimes, and junior optimes (corresponding to first, second, and third class honours in later British honours degrees).
- The acknowledgement of the 'senior wrangler'—the top student in the order of merit.

In January 1837, at the top of the list were William Griffin (senior wrangler), J. J. Sylvester (2nd wrangler), Edward Brummell (3rd wrangler), George Green (4th wrangler), Duncan Gregory (5th wrangler) and A. J. Ellis (6th wrangler). This list is typical of those that followed on throughout the Victorian era, where important mathematicians and unknowns appear side by side. The list is unimportant as a mathematical guide, but it was important socially. To be a 'wrangler' in the top class of the order of merit was a distinction that continued for life. If a student was the '14th wrangler' (say), then this would be as widely known as if it were branded across his forehead.

In the 1837 list we have a highly creative mathematician like J. J. Sylvester 'beaten' by someone unknown to the mathematical community. The order of merit—the grandfather of all league tables—did not indicate any research potential, and it was not supposed to. The mathematical tripos examination was primarily a contest for clever schoolboys who could jump through hoops at speed.

At the pinnacle of the order of merit was the champion student, the senior wrangler, a young man who held a fascination in the Victorian mind. He signified all that was good about the mathematical tripos and acted as a focus for the whole system. One contemporary remarked:[2]

> In my opinion it is this continuance of solving problems, this general course of not only acquiring principles but applying them, that at last makes the senior wrangler, who perhaps at the time is one of the most expert mathematicians in existence.

The senior wrangler was an early example of a 'celebrity' and became someone believed to have superior powers quite beyond the competence tested in the mathematical examination. Occasionally the system did identify future mathematicians and scientists. In the early 1840s the senior wranglers were R. L. Ellis (1840), George Gabriel Stokes (1841), Arthur Cayley (1842), and John Couch Adams (1843), a group who achieved fame in mathematical subjects, and who were still talked about by the end of the century as that 'illustrious quartet'. They were unusual, and a present-day mathematician would find it difficult to name other senior wranglers of the period. Ellis detested the Cambridge system, Cayley seemed unaffected by it, while Adams was caught up in the excitement of it all and thought that he had little chance of the top spot.

One thing was clear. The serious students coming up to Cambridge were rapidly moved into examination mode. There were examinations at every turn—on arrival and at the annual college examinations—and the whole procession culminated in the university-wide mathematical tripos examination at the end of ten terms, an examination held in icy rooms in the January of each year. The skills of solving problems and working quickly under pressure were all part of the Cambridge package for its students. If they succeeded, there would be a week-long set of examinations for the two Smith's prizes, and then there were the College fellowships to strive for. A fellowship gained a person status, income, and freedom from earning a living for at least seven years. If they were at Trinity College, the high flyers with a fellowship in prospect would face another batch of examinations nine months after the exertions of the mathematical tripos and the Smith's prize contest.

The tripos examinations of the 1840s spread over six days covering equal proportions of 'pure' and 'applied' questions (then called 'mixed mathematics'). The exam schedule was typically from Wednesday to Saturday with Sunday off, followed by Monday and Tuesday—five and a half hours each day, but six hours on Saturday. The examination papers contained questions on such subjects as astronomy, algebraic topics, the theory of integration, differential equations, mechanics, and the application of mathematics to such questions as the shape of the rotating earth. The examinations were of varying length, from nine to twenty-four questions, and in all, one hundred and seventy-seven questions were put before the students (see Box 1.1).

What is not conveyed by citing individual questions is the time dimension. To answer *all* questions completely on a paper would require superhuman qualities. This would not be expected, but the subtext generated by the competition was still 'speed'. While the mathematical tripos of the 19th century was described as a 'great writing race' by Augustus De Morgan, it was also remarkable in its wide coverage of mathematical topics.

To make success a reality, the private mathematical coaches came into their own by supplying tuition and examination tips. They stressed the practical acquisition of examination technique geared towards examination performance and, in that sole aim, they inculcated hard work. One of the last students to experience this regime wrote:[3]

not a day, not an hour was wasted; the perfect candidate should be able to write the bookwork automatically while his thoughts were busy with the rider, and the

Box 1.1: Some Cambridge examination questions

The questions at the start of examination week for honours were fairly straightforward. The first paper carried the rubric 'The differential calculus not to be used' and consisted of sixteen geometrical and algebraic questions of varying length, with the candidates being invited to answer as many or few questions as they wished. A quarter of the questions on the examination paper were allocated to 'problems', with the bulk of questions of bookwork type. One problem question was to:

> Shew that the sum of a fraction and its reciprocal is always greater than 2.
> How can we, consistent with this truth, assume that $2 \cos \theta = x + 1/x$?

A question that might have caused many to scratch their heads was a bookwork question once set by Duncan Gregory on the final day. Many of the questions on these examination papers were written in a prose style:

> If a rigid body be struck by any couple, the axis of the couple can never be the corresponding instantaneous axis of rotation, unless it coincide with a principal axis of the body. Shew also that, when this condition is fulfilled, the angular velocity round the principal axis is equal to the moment of the couple divided by the moment of inertia round the axis.

At the end of this paper, the end of the examination period, was a long question on the 'shape of the earth' to wish them on their way.

The level of the honours examination lay somewhere between the standard expected of the ordinary (poll) degree student and the Smith's prize candidate. The poll student might be asked practical questions in the mathematics section such as:

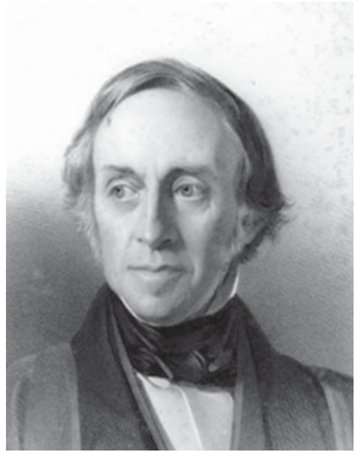
> Find the sum of $3\frac{5}{12}$, $7\frac{1}{2}$, $8\frac{2}{3}$, 4, and $2\frac{1}{4}$.

The questions set for the Smith's prize examination, a competition for the top students, were technically demanding. The opportunity to set them was an occasion for the professors to show off their erudition, and the questions demanded both bookwork knowledge and technical skill. They were challenging, even allowing for students being coached to answer them:

> The problem: 'To find the path of a body, acted on by gravity and moving in a medium of which the resistance is as the *2n* power of the velocity': was solved by Bernoulli as follows:
> Assumptâ indeterminatâ z, construatur area $\int (aa + zz)^{n-1/2}\, dz$ quae vocetur Z; sint autam co-ordinatæ curvæ quæsitæ x et y. Fiat $x = \int (zdz.\, Z^{1/4})$ et $y = \int (adz.\, Z^{1/4})$. Dico curvam quæ inde oritur esse quæsitam. Prove this construction.

fingers could be trained even when the brain was weary; above all, curiosity about unscheduled mathematics was depravity.

The Victorian era was spanned by the two great exemplars of the coaching trade, William Hopkins and Edward John Routh (see Box 1.2).



William Hopkins (1793–1866), early Victorian mathematical coach.

Box 1.2: Students of the coaches William Hopkins and E. J. Routh

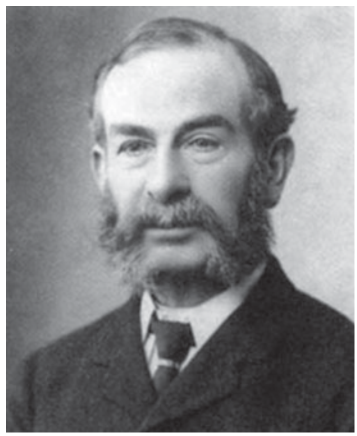
HOPKINS' PUPILS INCLUDED:

J. H. Pratt, P. Kelland, A. Smith, J. J. Sylvester, M. O'Brien, R. L. Ellis, G. G. Stokes, A. Cayley, F. Fuller, F. Galton, W. Thomson (Lord Kelvin), W. F. L. Fischer, H. Blackburn, I. Todhunter, N. M. Ferrers, P. G. Tait, W. J. Steele, E. J. Routh, and J. C. Maxwell.

ROUTH'S PUPILS INCLUDED:

J. W. Strutt (Lord Rayleigh), W. D. Niven, J. Stuart, C. Niven, W. K. Clifford, G. H. Darwin, J. W. L. Glaisher, H. Lamb, W. W. Rouse Ball, G. Chrystal, J. H. Poynting, K. Pearson, J. Larmor, J. J. Thomson, A. R. Forsyth, H. F. Baker, and W. McF. Orr.

Hopkins took a paternal interest in his pupils and achieved success after success during the early part of the Victorian period. For a handful of students the mathematical tripos held no terrors, and under the watchful eye of a Hopkins they succeeded and were enthused by mathematics. But, in taking thoroughness and efficiency to new levels, it was Hopkins' pupil E. J. Routh who dominated the coaching scene in the latter half of the century. The successful coaches taught their students by giving lectures to them in their rooms, marking their work, and above all focusing on those topics likely to appear in the examination. Routh knew what would 'pay' and what would not, and the best students opted to be under his guidance. In effect, the private coaches ran private colleges within the university.



E. J. Routh (1831–1907), later Victorian mathematical coach.

George Peacock criticized the 'unhappy system' of private tuition. He challenged the notion that mathematics was good medicine for all students and the rule that students had first to acquit themselves in the mathematical tripos examination before taking the classics degree. He saw all too plainly that the mathematical tripos was crammed full of subjects that resulted in an indigestible course of study, and a reduction in the previous wide coverage was proposed and accepted. His contemporary William Whewell argued strongly for student attendance at the lectures given by the professors who, he observed, had little input in the workings of the mathematical tripos, but otherwise he opposed changes to it. In 1848, the Board of Mathematical Studies was set up and reforms made, but Peacock could do little about the issue of private coaching.[4] It was recommended that the mathematical tripos examinations be in two parts, thus reducing the pressure brought about by a continuous battery of examinations one after the other—now there would be a few days between the two parts.

New 'technologies' came to the aid of the student. The Macmillan book empire, set up originally in Cambridge, was in its ascendancy in the 1840s, and expanded from one of pure bookselling to one of publishing as well. One of their first publishing ventures in mathematics was George Boole's *Mathematical Analysis of Logic* (1847), but they made most money from textbooks, and one of the first of these, Isaac Todhunter's *Differential and Integral Calculus* (1852) was a bestseller. Publishing textbooks became easier and more available to the student population. Todhunter exceeded all expectations with his edition of Euclid which sold over half a million copies.[5]

The requirements for a tripos student were really quite basic, as can be judged from Lord Rayleigh's student booklist of the 1860s: Todhunter's textbooks on differential calculus, integral calculus, algebra, conic sections, trigonometry, and geometrical conics. Also included were Ferrers' *Trilinear Coordinates*, Drew's *Analytical Statics* and *Dynamics of a Particle*, Herschel's *Outlines of Astronomy*, Salmon's *Conic Sections*, and Routh's *Rigid Dynamics*.[6]

The early Victorian period did see some collective movement in the direction of research and scholarship in mathematics. One outcome was the founding of *The Cambridge Mathematical Journal* in 1837 and its successor, *The Cambridge and Dublin Mathematical Journal*, in 1846. As described in Chapter 7, these gave the young mathematicians an opportunity to see their work in print and get them used to publication.

While the Cambridge journals had an international dimension and enjoyed the support of a few continental mathematicians, they also brought together students and fellows from the different colleges of Cambridge. In the 1840s teaching was college-based and a man had no necessity to mix with students from other colleges. The Cambridge journals performed the useful function of removing this insularity and, when *Dublin* was added to the title, of enlarging the research base in Britain. In 1845 the British Association for the Advancement of Science came to Cambridge, and Peacock handed over the reins to the incoming president, Sir John Herschel, who praised the 'green shoots' of mathematical research that Britain was beginning to produce.

John Couch Adams (1819–92), Lowndean professor.

The importance of mathematics was brought home to the Victorian public in the 1840s by the discovery of the planet Neptune. This scientific triumph was claimed by both England and France and was given wide coverage in the media, but it was the method of discovery that brought mathematics to centre stage. The recently graduated senior wrangler John Couch Adams discovered the planet not by searching for it in the night sky, but by mathematics. Using Newton's theory of gravitation, he discovered it at the 'tip of his pen', and it was this power of mathematics that was proclaimed in the newspapers and pulpits around the country.

The settled Victorians: the 1850s and 1860s

In 1850, a Royal Commission was appointed to look into the workings of both Oxford and Cambridge Universities. The resulting Cambridge University Act (1856) gave a new impetus to the creation of the University as something more than a collection of autonomous colleges. A new form of governance was given to the University and the powers of the individual colleges were reduced. The need to declare allegiance to the Church of England for admission to a degree was abolished for all degrees except divinity. New chairs were created, such as the one gained by converting the previously existing Sadleirian college lecturerships in algebra into the Sadleirian chair of pure mathematics.

The road to research proved bumpy. Through financial problems, *The Cambridge and Dublin Mathematical Journal*, which William Thomson had launched with such brio in 1846, collapsed in 1854. It was rebranded in the following year as *The Quarterly Journal of Pure and Applied Mathematics* (see Chapter 7). After a rocky start, when it was even doubtful if this would continue, it made a long run until 1927, for many years under the editorship of the Cambridge don J. W. L. Glaisher. During its first years it provided a vital link in the establishment of a research ethos in British mathematics, but this ethos was fragile. W. P. Turnbull, who gained a Trinity College fellowship in 1865, published a text on analytical geometry in 1867, but said that the 'book was produced at a time when abstract thought was rather at a discount, for physical research was in the ascendant'.[7]

J. W. L. Glaisher (1848–1928), editor of *The Quarterly Journal* and *The Messenger of Mathematics*.

It was the mathematical tripos that mattered most at Cambridge, and not least the order of merit and the senior wranglership: it was a Cambridge affair that in hindsight now seems somewhat parochial. Some admired the stability of the system, as did the theologian F. J. A. Hort in the 1850s, who bemoaned that there had been no Trinity College senior wrangler in eleven years: 'I feel a proper pride in the mathematical tripos and senior wranglership as great existing institutions'.[8] Hort was a man who sat more than his fair share of Cambridge examinations and held the system in great respect. But what are we to make of the rebellious Leslie Stephen, a mathematics tutor in the 1850s who ridiculed the mathematical tripos and wrote, 'To this day I do not realise—though on purely intellectual grounds I accept—the fact that even a senior Wrangler is made of flesh and blood'?[9] In the Cambridge *Student's Guide* of 1863, J. R. Seeley summed up its position:[10]

> The Mathematical Examination of Cambridge is widely celebrated, and has given to this University its character of the Mathematical University *par excellence*.

The 'reading men' who took the honours degree represented about one-fifth of each year's intake of students. The ordinary or 'poll' degree students were required to study mathematics as well, but their standard of mathematics was undoubtedly low. This was a reflection on the public schools, where mathematics occupied a very small part of the curriculum and where the emphasis was on the teaching of classics. One veteran mathematics tutor at Cambridge reported at the beginning of the 1860s on 'Euclid got by heart and not understood; arithmetic worked by rule of thumb, without any understanding of the simplest first principles; algebra, a chaos of confusion'.[11] As to the working of the system, the student culture offered another viewpoint. It was said about poll examinations that:

> the most common method [of cheating] of all was to take in many of the most likely answers, especially propositions in mechanics, Hydrostatics, in Euclid and the like, ready written out, and to produce them from the pocket... Twenty examiners, all parading the Senate House, and all looking sharp too, would not be too many to detect the numerous tricks implied to hoodwink an examiner.[12]

Arthur Cayley (1821–95), Sadleirian professor.

Notwithstanding this, the Cambridge system of education was held in the highest regard, especially as many products of it were included in the 'Upper Ten Thousand' who ran the country. While Lord Palmerston naturally preferred patronage to examinations as a basis for sound appointments, he did acknowledge the value of mathematics, and especially Euclid, which he thought excellent training for a diplomat.

William Everett, an American student who spent three years at Cambridge in the 1860s, noted the characteristics of the mathematical education he received and its continued reliance on Newton and Euclid:[13]

> Englishmen hate going back to first principles, and mathematics allows them to accept a few axiomatic statements laid down by their two gods, Euclid and Newton, and then go on and on, very seldom reverting to them. This system of mathematics developed in England, is exceedingly different from that either of the Germans or the French, and though at different times it has borrowed much from both these countries, it has redistilled it through its own alembic, till it is all English of the English.

Whewell's idea of bringing the professors' lectures into contact with undergraduates went unfulfilled, except for ordinary degree students who for a term attended a professor's lectures by compulsion. Professors Cayley and Adams regularly gave their erudite lectures to audiences of two or three—a number that would occasionally include each other.

When reform of the mathematical tripos was considered in the 1860s, the newly installed Sadleirian professor, Arthur Cayley, engaged in debate with George Airy, the Astronomer Royal and former Lucasian professor of mathematics at Cambridge. Cayley thought of his subject independently of any students, while Airy's thinking was shaped by the ideals of the university as a teaching institution. It was Cayley's ill-advised sentence: 'I do not think everything should be subordinated to the educational element',[14] which caused Airy the greatest consternation. Airy wrote back:[15]

I cannot conceal my surprise at this sentiment, assuredly the founders of the Colleges intended them for education (so far as they apply to persons in *statu pupillari*), the statutes of the University and the Colleges are framed for education, and fathers send their sons to the University for education. If I had not your words before me, I should have said that it is impossible to doubt this.

When Airy was a student at Cambridge in the 1820s, the University had been solely a teaching institution. With the new professors appointed in the 1860s, the seeds of change were planted, but a research culture in mathematics had yet to grow and mature.

Box 1.3: The Victorian mathematical professors

LUCASIAN PROFESSORS (MATHEMATICS, 1663)

1828–39	C. Babbage
1839–49	J. King
1849–1903	G. G. Stokes

PLUMIAN PROFESSORS (ASTRONOMY AND EXPERIMENTAL PHILOSOPHY, 1704)

1836–83	J. Challis
1883–1912	G. H. Darwin

LOWNDEAN PROFESSORS (ASTRONOMY AND GEOMETRY, 1749)

1837–58	G. Peacock
1859–92	J. C. Adams
1892–1914	R. S. Ball

SADLEIRIAN PROFESSORS (PURE MATHEMATICS, 1860)

1863–95	A. Cayley
1895–1910	A. R. Forsyth

(MECHANISM AND APPLIED MATHEMATICS, 1875)

1875–90	J. Stuart
1890–1903	J. A. Ewing

The high-Victorians unsettled: 1870–1901

By the beginning of the 1870s, Britain was facing increased economic competition from Germany and the United States of America. There was a concern that the scientific base of new developments could be eroded and that Britain would lose her leadership in the world. The Devonshire Commission on Scientific Instruction and the Advancement of Science sat during 1872–75 and produced a voluminous report. The Oxford and Cambridge Commission of 1877 resulted in a University of Oxford and Cambridge Act, which enforced further changes in the governance of the university following the first modern reorganization in 1856. The first steps towards the higher education of women began in the 1870s, and a decade later a woman was recognized as the equivalent of a 'wrangler', though the formal admittance to a degree was still a long way off.

Major reforms in the mathematical tripos came into operation in 1873. The syllabus now included the introduction (and reintroduction) of such topics as the mathematical theory of elasticity, heat, electricity, waves, and tides, with these new specialisms arranged in divisions that students could select for their study. Karl Pearson praised the mathematical tripos examination of the 1870s. He liked it for its broad sweep, for its being '*not* specialised, but [giving] a general review of the principia of many branches of mathematical science', and he valued the 'problems', which forced the private coaches to deal with such questions in their classes. He observed that this essence of mathematical research was missing in the much-heralded German system, which he saw as laying the emphasis on the teaching of theory.[16]

But overall, these reforms of the mathematical tripos were not a success and even in their first year of operation this failure was apparent. Drilled in examination technique by their coaches, students quickly learned that the art of cherry-picking across the subject divisions was an effective way of amassing marks. This led to a superficial knowledge of a wide range of subjects, rather than knowledge of particular subjects to any depth. Drastic action was required. In May 1877 a large and influential University syndicate was appointed.[17] High on its agenda for discussion were:

- Whether the order of merit should be retained.
- The status of the senior wrangler.
- How to cope with the increase in mathematical knowledge, and whether the mathematical tripos could, or should, cover the whole of mathematics.
- Whether the honours students should be allowed to sit the mathematical tripos examinations in June, or keep to the traditional January examinations.

Reaching an agreed radical solution was impossible. Syndicate members were successful products of the very system they were investigating, and there would inevitably be a strong tendency to preserve their 'golden age'. Of course, the private coaches also had a powerful incentive for maintaining a system which benefitted them financially.

The 1873 increase in subjects caused problems in the running of the order of merit, for there was little common ground on which to compare the performance of individual students. Some dons were in favour of the system whereby students were divided into classes and then listed alphabetically. But this impinged on the awarding of college fellowships, where a high position in the order of merit was a traditional criterion for election in most colleges.

An elaborate scheme for reform was accepted towards the end of 1878, but it represented a compromise which pleased few members of the University Senate and resulted in a most complicated structure.[18] The order of merit and the position of senior wrangler were both retained and would be decided on the results obtained in an examination held in June, and not in January as tradition had demanded. After this examination, only the wranglers would go on to an advanced part in the following January, so there was to be a January examination. In their number would be the 'professed mathematicians', or those going on to a career in mathematics. In the advanced part the results were given by alphabetical surname order in class divisions. It was too much for some of the diehards, and especially the coaches. Routh was said to have exclaimed: 'They will want to run the Derby in alphabetical order next'.[19]

In 1882 two tripos lists were issued, one in January for the old system, and one in June for the new system. The senior wrangler under the old regulations was R. A. Herman, one of the last private coaches, who later taught G. H. Hardy.

Attention was turning towards research being part of the university's mission. Five university lectureships in mathematics were created in 1883: the first appointed were J. J. Thomson, A. R. Forsyth, W. H. Macaulay, R. T. Glazebrook, and E. W. Hobson, and each received a stipend of £50. But how was research to be done? Thomas Muir wrote of the Scottish universities, that while:

> we recognise two of the functions of a University—*instruction* and *research*, we ignore, so far as mathematics is concerned, a third and equally important function—*instruction in research*.[20]

What could be said of Scotland applied equally to Cambridge. Instruction in research was not provided in anything like the way it was in Germany, where the driving force in pure mathematics was Felix Klein. The most obvious candidate for leading research at Cambridge was Arthur Cayley, the Sadleirian professor of mathematics. Cayley did have his protégés in J. W. L. Glaisher, W. K. Clifford, A. R. Forsyth, and H. F. Baker, and he gave assistance to a number of promising students, including women, who were beginning to arrive on the scene in the 1880s. His main interest was invariant theory, but the leadership in this area had passed to Germany, and the particular way he approached it—by collecting specimens in the manner of the natural scientist—was falling out of favour. Baker started on this tack but dropped it fairly quickly, while Forsyth, a loyal apostle in the 1880s, took up other paths. By the 1880s Glaisher was forced to admit that Britain had leaders but no followers. Cayley was, in the end, a 'General without Armies'.[21]

G. H. Hardy identified the 1880s as the time when the mathematical tripos was at the zenith of its reputation in the public eye, but one that coincided with research in pure mathematics in England being at its lowest ebb.[22] The lone star in pure mathematics at Cambridge was the ageing Cayley.

Quite the opposite was the case with applied mathematics and theoretical physics. A product of the mathematical tripos of the 1840s, George Gabriel Stokes distinguished himself in mathematics generally, but he is really noted for his contributions to mathematical physics. Apart from Stokes, who was actually born in Ireland, it is notable that many of those who arrived at Cambridge to sit the tripos had already distinguished themselves in the educational system in their native Scotland. From a remarkable social family group, William Thomson and James Clerk Maxwell made their way to Cambridge to top up their education in the 'Holy City'. Thomson was a child prodigy, writing original papers on Fourier series as a 16-year old, but he quickly turned his attention to mathematical physics. In fact he was actually disdainful of pure mathematics, as shown by the frustration he expressed to Hermann von Helmholtz in 1864 that such a talent as Cayley's should not apply itself to the mathematical problems in the theory of electricity:[23]

> Oh! that the CAYLEYS would devote what skill they have to such things [Kirchhoff's theory of electrical conduction] instead of to pieces of algebra which possibly interest four people in the world, certainly not more, and possibly also only the one person who works. It is really too bad that they don't take their part in the advancement of the world.

Besides Thomson, there was the genius of Maxwell, also a mathematician who devoted himself to physical theories. On the experimental side the Cavendish laboratory was created at Cambridge in the early 1870s. This vigorous enterprise had Maxwell as its first director; he was followed by Lord Rayleigh and then J. J. Thomson. Such luminaries as Rayleigh (on the physics of sound),

A student at Newnham College in the 1880s.

Thomson (on mathematical physics, and specifically the discovery of the electron), G. H. Darwin, the second son of Charles Darwin (on geodesy), and J. Larmor (on the theory of relativity) helped to gain Cambridge a worldwide reputation for excellence in mathematical physics in the late-Victorian period.

In 1886 a newer two-part mathematical tripos was created. A two-year Part I decided the order of merit, and a Part II taken a year later offered the advanced subjects.[24] Both exams were scheduled for the summer, and the famous January examination became a thing of the past. The new Part I was a technical course; indeed, the whole idea of mathematics as the underpinning of a liberal education for all students had proved impossible to maintain. It was a very different mathematical tripos from that of the beginning of the Victorian period, when mathematics had no competing subjects and students had little choice of what to study. Towards the end of Victoria's reign the number of students opting for the mathematical tripos course fell rapidly. In the 1840s, an average of one hundred and twenty-four mathematical tripos students graduated each year with an honours degree, but by the 1890s there were only ninety-two.

In 1890 G. T. Bennett graduated as senior wrangler and winner of the first Smith's prize. These prizes were now awarded for dissertations, and so impressed was Cayley by Bennett's paper on number theory that he communicated it to the Royal Society for publication.[25] But while Bennett was the *official* male senior wrangler, it was Philippa Fawcett's performance that electrified the student population when she graduated 'above the Senior Wrangler' and, both celebrated and disparaged, she was eulogized in doggerel:

Hail the triumph of the corset,
Hail the fair Philippa Fawcett.

Philippa Fawcett (1868–1948).

The year-on-year procession of males in the order of merit had at last been topped by a female scholar. Women could study at Cambridge, but they could not be admitted to a degree and membership of the university until 1948, when the first to be admitted was the Queen Mother, with an honorary doctorate. By Philippa Fawcett's time the state of the mathematical tripos was again under attack, and the attack would continue until the system eventually changed.

In George Bernard Shaw's play *Mrs Warren's Profession*, Vivie gave voice to the curious phenomenon that the mathematical tripos had become by the end of the 19th century:[26]

> do you know what the mathematical tripos means? It means grind, grind, grind for six to eight hours a day at mathematics, and nothing but mathematics. I'm supposed to know something about science; but I know nothing except the mathematics it involves. I can make calculations for engineers, electricians, insurance companies, and so on; but I know next to nothing about engineering or electricity or insurance. I don't even know arithmetic well.

Tensions existed between the teachers of mathematics and 'active mathematicians' who researched the subject. The latter could not believe in teaching a system that was dominated by an examination consisting of artificial problems which could only be justified by being good mathematical tripos examination questions. G. H. Hardy believed that, since it dominated Cambridge mathematics, and was in turn dominated by an examination which consisted of artificial questions about subjects of no interest to professional mathematicians, the mathematical tripos stifled real mathematical research. He thus concluded that the whole thing should be abolished.[27]

Aftermath

Queen Victoria died at Osborne on the Isle of Wight on 22 January 1901, but 'Victorian mathematics' at Cambridge continued a little longer. The big fight in the cause of mathematical tripos reform took place in 1907. The majority of active mathematicians at Cambridge were in favour of the abolition of the order of merit and the coveted title of the senior wrangler, but there was a minority who opposed the reforms. One private coach, a protégé of E. J. Routh, thought that the proposed reforms would mean the end of mathematics at Cambridge.[28]

The vote was put to the whole electorate of Cambridge M.A.s. The voting took place in February 1907, and about 55 per cent were in favour of reform. The turnout was only 20 per cent, no doubt reduced by the requirement that voters had to attend Cambridge in person. It was a close call, but in a first-past-the-post voting system 'one is enough'. The last examination under the old regulations was held in 1909.[29] It was truly the end of an era. The institution of the private coach melted away, and in the tumultuous events of 1914–1918 the mathematical tripos, which had reigned supreme during the Victorian period, became a distant memory.[30]

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A caricature of Henry Smith, Savilian professor of geometry from 1861 to 1883.

CHAPTER 2

Mathematics in Victorian Oxford

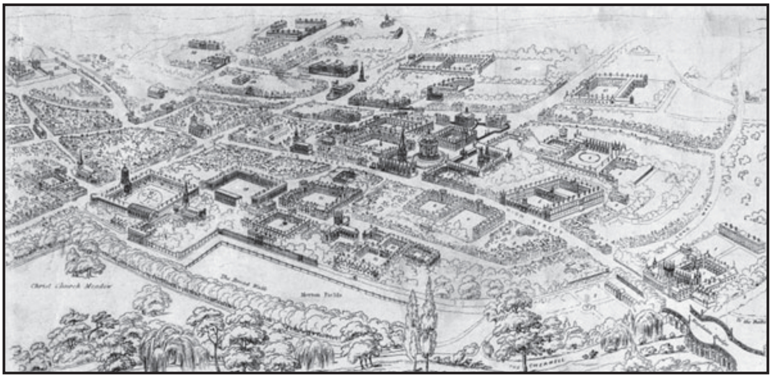
A tale of three professors

KEITH HANNABUSS

Whereas Cambridge was uniformly regarded as the centre of both British mathematical education and research throughout the 19th century, the curriculum at the University of Oxford was geared more towards the study of classics and the humanities. Thus, while mathematics was not unimportant at Oxford, it did not have the same dominance over the course of study as at its rival institution in the Fens. Indeed, throughout the Victorian period, Oxford mathematicians had to strive to establish a mathematical culture as prevalent as that which existed at Cambridge. The key figures in this endeavour during this period were the three holders of Oxford's most prestigious mathematical chair, the Savilian professorship of geometry, which had been founded by Sir Henry Savile in 1619. This chapter documents the changing fortunes of mathematics during the Victorian period at Britain's oldest university, and the principal mathematicians involved in this process.

In 1837 Oxford was a small and relatively isolated city, dominated by the University. Its north-eastern boundary followed roughly the line leading from Magdalen College and Wadham College through St Giles Church to the Radcliffe Observatory. (Little changed for almost twenty years, Magdalen Bridge is at the bottom right-hand corner of the figure overleaf, and the Radcliffe Observatory is near the middle of the horizon, with St Giles Church to its right and slightly lower. Beyond the visible buildings there is open country. From 1855 the

University Museum was built roughly at the right-hand edge of the horizon, and the Norham estate beyond that.) The University was still largely a mix of a finishing school for gentlemen and a seminary for the Anglican clergy. Students had to sign the 39 articles on matriculation, so that Jews, Catholics, Nonconformists, and other dissenters were effectively excluded. Moreover, this requirement could not be postponed until graduation as at Cambridge, a possibility that allowed non-Anglicans like Sylvester to study there, as long as they did not take their degree.

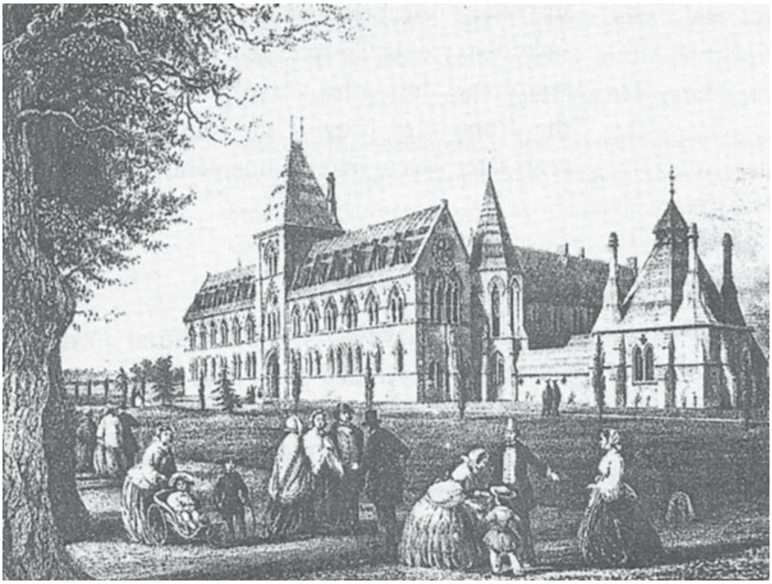


A bird's-eye view of Oxford University and city, 1850.

With a few exceptions—professors, heads of houses, and a small number of lay fellows—dons were required to take holy orders within around seven years, first as a deacon and then as a priest, and they were not allowed to marry.[1] The typical career for a bright undergraduate would be to obtain a college fellowship soon after graduation, proceed to ordination and then, assuming he wished to marry, move to a suitable living when one fell vacant. These livings were usually in remote villages where the parish demands were small and they could continue their scholarship and research. This system ensured that there were generally fellowships for the promising young graduates to start a career—although the opportunities were rather greater in classics than in mathematics—but its disadvantage was that it was difficult to develop an academic profession in the modern sense.

During Victoria's reign all this changed. The opening of the Great Western Railway line in 1844 eased the isolation. (It is a measure of Oxford's previous seclusion that one of the Oxford–London express coachmen turned out to have a wife and family at each end of his itinerary.[2]) In 1855 the University commenced construction of the University Museum as a centre for the sciences, including mathematics, on a site beyond the old northern boundary. By the time of the Museum's opening in 1860, the city too had started to extend further north, with developments like Park Town, and plans for the Norham Manor estate between Norham Gardens and Norham Road.

Two Royal Commissions that reported in 1854 and 1877, plus the ensuing acts of Parliament, abolished the religious tests and celibacy requirements; this parliamentary intervention came although the University received no public money at all until further reforms in 1923. With the relaxation of the celibacy



The new University Museum in 1860.

rule, and consequently a larger number of academic families, the city continued to expand. Where in 1860 the planned Norham Manor estate formed no more than an island of houses in the open countryside, it soon became the portal to a much larger development to the north and west.

The honour schools had started in 1800 as a more demanding alternative to the pass schools, though only three colleges (Balliol, Christ Church, and Oriel) insisted that all students must read for honours. Initially the honours were awarded in classics (*In Literis Humanioribus*) and mathematics (*In Disciplinis Mathematicis et Physicis*), which covered pure and applied mathematics. In 1849 the University decided to add honour schools of natural science and modern history with jurisprudence to the existing schools, and with the introduction of the new examinations in 1853, the mathematical honours were renamed *In Scientiis Mathematicis et Physicis*; the new mathematical honour moderations, first examined in Easter term 1852, were just *In Disciplinis Mathematicis*. In the course of the century the numbers taking honours in all subjects rose from under one hundred to nearer five hundred.

The dominance of classical studies was evident not only in student numbers, but in elections to fellowships: in 1853 it was reported that three-quarters of those with first class honours in classics got fellowships, compared with only one-third of those with first class honours in mathematics.[3] Although mathematics was a much smaller school than classics, its numbers initially rose more or less in line with the total until 1850, when they levelled off and most of the expansion went into the new natural science school. The total number of honours degrees more than trebled during the second half of the century, and the number of honours gained in the two schools of mathematics and natural science remained at a fairly steady 15 per cent of the total, but of those the number of honours