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ROBERT WOODHOUSE AND THE EVOLUTION OF CAMBRIDGE MATHEMATICS

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Robert Woodhouse's lifetime, 1773–1827, is often characterized as the nadir of British mathematics.[1] In that view, the country of Newton was clinging desperately to his coat-tails whilst Continental mathematicians forged on with novel and important work in mathematics and the physical sciences. Although Woodhouse briefly held the Lucasian Chair, the esteemed position of Newton at Cambridge, his work sought to introduce Continental mathematics to the university and reduce the blind allegiance to her most famous alumnus. Men prior to Woodhouse, such as Edward Waring and John Landen, had introduced analytical methods to England, but Woodhouse was the first to do so with an eye to incorporating them into the Cambridge curriculum. By the time of Woodhouse's death, undergraduates did learn differential notation, and analytical developments on the Continent were increasingly disseminated and incorporated into the sciences, albeit in a diluted form. Nonetheless, undergraduate studies at Cambridge remained focused on the training of students for religious and gentlemanly positions, discouraging original research. In this regard, Woodhouse was situated in a transitory period and his career is comprehensible only in light of the tensions between reform and continuity within British mathematics.

In addition to holding the Lucasian Chair from 1820 to 1822, Woodhouse was the Plumian Professor from 1822 to 1827 and the first director of the Cambridge Observatory when it opened in 1824. Nevertheless, he was isolated from many of the main mathematical figures of his time at Cambridge. Overshadowed early in his career by Samuel Vince and John Wood, and later by William Whewell, George Peacock and George Airy, Woodhouse was never fully established within one community. This seclusion was exacerbated by the isolation of Cambridge University itself at the turn of the nineteenth century. It was a collection of relatively insular colleges, whose leaders had been promoted almost exclusively from within. Furthermore, the mathematical curriculum was overwhelmingly conservative, emphasizing memorization and examination over original research, and maintaining a complacent attitude toward foreign developments.

Paradoxically, the historiography has focused disproportionately on novel mathematical investigation in this era, despite this being an almost non-existent part of the Cambridge system. Dons, including Woodhouse for the majority of his career, were more concerned with the teaching and training of students than with the development of their field. Nonetheless, historians have primarily examined work in analysis and algebra done by a small number of mathematically-gifted students which would serve as the basis for developments throughout the century. Because of their later

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influence, these research-driven students and their associations such as the Analytical Society have dominated the literature and served as the explanation for curricular changes. Although the students involved were generally first-rate mathematicians, they remained a small minority and few had any impact upon studies at Cambridge. In this research-focused historiography, Woodhouse functions either as an ineffective forefather for reformers like the Analytical Society or as a harbinger of modern algebra developed fully later in the century.[2] At the time of his death, however, he was best known for neither of these, but rather for his astronomical work.

In this article, I move away from the traditional focus on Woodhouse's early publications and the ways they influenced the development of algebra and analysis. Instead of tracing the mathematics background and context for his 1803 *Principles of analytical calculation*, the text most often cited by historians regarding Woodhouse's influence, I turn to his subsequent work, focusing on pedagogy and the applications of analytical mathematics. I argue that it is through these later texts and his increasing presence within the university that he would be able to introduce analytic methods into Cambridge. By combining his later writings with the early research, we can contextualize his career as a whole, understanding his own important shift from principles to applications and how this allowed him to effect change in the undergraduate curriculum. In doing so, I show that Woodhouse's gradual introduction and careful framing of analysis proved to be at least as much a factor in the evolution of studies as novel mathematical investigation itself.

To place Woodhouse within this period in Cambridge mathematics, I first trace his shift from research in mathematics to writing influential, pedagogically-informed texts. Then I turn to the so-called analytical revolution and describe the role that Woodhouse played in the complex changes that took place in the Cambridge curriculum. Finally, I describe Woodhouse's work on astronomy and his increasing prominence at the university, in the context of the general introduction of the physical sciences to Cambridge. I ask not only how he exerted his new power but also how his influence and legacy were so quickly forgotten after his death. It is not a triumphant story, by any means, but it is a story of an overlooked man who played a crucial role in an important moment in the history of mathematics.

1. WOODHOUSE'S EARLY DEVELOPMENT

Robert Woodhouse, born to a woollen-draper of the same name in Norwich, spent eight years at North Walsham School and was also taught by George Morgan at New College in Hackney.[3] After his preparatory schooling, Woodhouse was admitted as a pensioner to Gonville and Caius College, Cambridge, in May 1790, a common collegiate choice for Norwich men. Little is known about his studies at the university, but as he graduated Senior Wrangler and the winner of the first Smith's prize — the two most prestigious undergraduate mathematics honours at the time — it was clear that he was skilled in the traditional mathematical curriculum required by the Cambridge examiners. After his 1795 graduation, he took up a fellowship at Gonville and Caius and began reviewing mathematics for the *Monthly review*.[4] In this position, he began to analyse the French mathematics of Lagrange, Laplace and Lacroix, as well as British authors. The articles are a rich source for his views, and indicate an early shift away from the synthetic style prevalent at Cambridge, a movement that would assert itself boldly in his 1803 *Principles of analytical calculation*.

In the *Principles*, Woodhouse argued that the calculus should be built up from the analysis of functions rather than from the geometry of motion. Focusing on the commodiousness of Lagrange's method of the development of functions, he cited as evidence the failure of many other skilled mathematicians to give explications of Newton's theory that adequately avoid the criticisms of Berkeley's *Analyst*.[5] He was careful to assert that this new method of Lagrange was not the only basis for the calculus but rather one that led most clearly to the conclusions of the calculus.

In shifting away from geometrical proofs, Woodhouse controversially reduced the concepts of motion and fluxions to a consequence of rather than a justification for the calculus. Nonetheless, he did not portray his treatise as radical, and indeed his only mathematical innovation was correcting the mistakes of Lagrange's method.[6] He ensured that the *Principles* would be seen as conservative through two strategies: first, he was explicit in his criticisms of the French, showing readers he was not uncritically introducing their methods; second, he carefully built up the development of functions, showing the technique relied on the expansion of the meanings of symbols commonly understood.[7] That is, Woodhouse tried to convince his readers that one could develop all the conclusions of the calculus from logically expanding the meaning of uncontroversial operations.[8] The success of these strategies is evinced both by the lack of significant outcry against the book and by the degree of success Woodhouse enjoyed at Cambridge directly after its publication.

Woodhouse's reversal of the traditional synthetic approach could pass without much fanfare for another and more important reason: it was rarely studied by students. Wood and Vince's texts on mixed mathematics were still widely used, and by the time Woodhouse's recommendations were generally accepted, other textbooks were in circulation. This does not mean that Woodhouse did not intend his book to be useful for students; he mentioned them in the preface, and his general aim was to provide grounding in the analytical methods for those unacquainted with any of the recent developments. In practice, the greater impediment to its use was that by 1803 students were already learning mathematics solely for performing well on the university honours examination. The examination — called the Tripos — determined graduation honours, fellowships and appointments to clerical posts.[9] Preparation for its questions had already led to a system of private tutoring. The questions would usually require the student to recall proofs of Newton and Euclid, often involving the application of basic mathematics to physical situations. Because of the power and autonomy of individual colleges, the examination — far more than professorial lectures — provided the university's greatest impact on undergraduate studies. Under this scheme, university lectures and collegiate tutors could be ignored, as long as the pupil had a sufficiently good 'coach' to prepare him for the examinations. Not every student could afford (or desired) a private tutor and they were not deemed essential for the examination until at least the 1820s.[10] Nonetheless, the system had taken hold by 1803 and discouraged mathematical investigation that would not help in the Tripos.

Because of the examination system, the *Principles* was largely ignored by students, and Woodhouse's arguments for analysis had little immediate effect upon the curriculum.[11] Woodhouse understood the system well enough to know that to effect curricular change he would have to portray analysis as fit for the Tripos examination, and his later texts would fulfil this task. Taken within this larger picture, the *Principles* served the crucial role of justifying the validity of analysis to Britons unfamiliar with the methods. To understand Woodhouse's influence, however, we must turn to his publications and career after 1803.

2. A NEW PEDAGOGICAL FOCUS

After the publication of the *Principles*, rather than being sidelined as a radical, Woodhouse steadily rose within the ranks of Cambridge over the next two decades. Increasingly, he turned to the issues of pedagogy and it is in his later writings that he would have his greatest influence at the university. His legacy has been disproportionately attributed to his early work only because of the historiography which emphasized original research over the standard curriculum.

In 1804, Woodhouse was appointed senior fellow within the college, and lecturer in mathematics within the university, a post which he held until 1813. Although many of his peers were looking for religious appointments, Woodhouse remained involved at Cambridge throughout his life.[12] In addition to lecturing, he took on an increasingly active role at Gonville and Caius, becoming the college steward in 1808, the registrar in 1811 and the bursar in 1814. Gradually working his way up the hierarchy, he would become president of the college — second only to the master — in 1821. At this point, also holding the Lucasian Chair, he had reached one of the highest levels within the college and university, a career that was to culminate in his appointments as the Plumian Professor in 1822 and director of the Cambridge Observatory in 1824.

After 1803, there was a marked shift in the kinds of mathematics Woodhouse would write. He became focused on astronomy and trigonometry and the application of analytic methods to those fields. This coincided with his own appointments as a teaching officer within the university, positions he took very seriously.[13] Perhaps aware that his lectures would remain less relevant than examination coaching, Woodhouse wrote treatises that presented analytic mathematics as appropriate for Tripos questions. One such treatise traced the historical development of the calculus of variations from the Bernoullis to the present. In a marked shift from the *Principles*, his aim in the *Treatise on isoperimetrical problems and the calculus of variations* was not to justify the analytic method but rather to show how it was developed because of its ability to solve problems successfully.[14] By portraying the development through problems, he implicitly set out how one uses the calculus. The treatise ends appropriately enough with dozens of problems for students to tackle themselves. This treatise is a fascinating resource for historians of the calculus even today, and much work remains to be done on it. For my purposes, it is important because it made itself doubly relevant to students' Tripos preparation: Woodhouse showed how the development of the calculus of variations was intimately related to a series of tangible problems — a minimum requirement for inclusion on the examination — and also provided many such problems as examples from which coaches and moderators could draw.

By approaching the calculus historically, Woodhouse portrayed the subject as a gradually refined tool for solving a series of problems. This theme was hardly restricted to the calculus: astronomy was the story of the perfection of the field and trigonometry exhibited the gradual refinement of its methods through the move away from geometry. Instead of the foundational approach, he now portrayed the subjects as complete entities to be studied, an approach more in line with the typical Tripos preparation. This represented a shift away from original investigation to treatises that emphasized the ability of analytic methods to answer questions in mixed mathematics.

This power of analytic methods would be demonstrated most successfully in his 1809 treatise on *Plane and spherical trigonometry*. Twenty-four years later Peacock would say that this book "more than any other work contributed to revolutionize the mathematical studies of this country".[15] In this treatise, Woodhouse took an algebraic definition of sine and cosine as his starting point, and from these deduced all of trigonometry.[16] By this time, he did not bother justifying his decision to eschew geometric and synthetic methods, simply dismissing them in the preface as less useful than analytic methods, and noting that they did not have an exclusive hold on perspicuity and logical exactness. Woodhouse did still have a scattering of diagrams and made references to Euclid, but all his demonstrations relied solely upon analysis.[17] He directed readers to his previous writings and those of Playfair, Ivory and others in the *Edinburgh Review*. Perhaps some of its popularity for Tripos preparation can also be explained by its worked problems. He gave multiple methods for solving the examples, allowing students to use whichever was easiest.[18] He explicitly differentiated this text from the *Principles*: it was not for explaining "the principles of the construction of the Trigonometrical Canon" but for "giving rules for practically constructing it with as much ease and conciseness as possible".[19] The text proved popular enough to warrant four more editions within Woodhouse's lifetime.

The *Trigonometry* and the *Calculus of variations* were notable for their incorporation of recent mathematical developments into the format most useful for Cambridge students. Although other contemporary authors arranged their texts around the application to questions, Woodhouse was the first to incorporate analysis into this system. By presenting the analytic tools in the *Trigonometry* and *Calculus of variations* as suitable for solving Tripos-like questions, he made them attractive to tutors and students preparing for the examination. As we will see, this proved a critical difference between their incorporation into the curriculum and the earlier lacklustre response to Woodhouse's *Principles*.

Woodhouse's increasing use of foreign notation and analytic methods was not universally appreciated in the conservative environment of Cambridge. Peacock said that Woodhouse's *Trigonometry* was "opposed and stigmatized by many of the older members, as tending to produce a dangerous innovation in the existing course of academical studies, and to subvert the prevalent taste for the geometrical form of conducting investigations".[20] Whewell noted that "Even Vince had constantly people making attacks upon him".[21] Despite criticisms from the older dons, the success Woodhouse enjoyed within the university suggests that he had amiable relationships with the elder generation.[22] It would be Woodhouse's connections to the younger generation that would prove more decisive for the changing of studies at Cambridge, however. Woodhouse undoubtedly faced criticism during his career, and his ability to maintain support of both generations while proving analysis fit for Cambridge mathematics examinations was one of his greatest accomplishments.

3. WOODHOUSE AND THE "ANALYTICAL REVOLUTION"

That 1806–18 was an important transitional period is best exemplified by the fact that Woodhouse could publish an exclusively analytical text for students in 1818 whilst in 1806 he believed the generality of Englishmen to be ignorant of these methods.[23] Many historians, as noted earlier, have explained this shift by looking at the research of a small group of undergraduates, most of whom were affiliated in one way or another with the short-lived Analytical Society. The important work of this small group, however, did not reflect the university as a whole at the time, and their work could have been understood by only a tiny number of students. Recently, Harvey Becher and Andrew Warwick have reversed this trend and reformulated the analytical revolution in terms of pedagogy. In particular, Warwick's work has traced the difficulties of changing the studies of undergraduates who are focused nearly exclusively on their preparation for the mixed mathematics questions of the Tripos.[24] The mathematics in the Tripos was not necessarily intended to give students a solid or complete mathematical background, but rather to train them to be 'gentlemen'.[25] The system of having recent wranglers serving as moderators ensured consistency and maintained the conservative approach to the subject. Through looking at the social backgrounds and corresponding politics of the Analytical Society's members, Becher has outlined how the only effective changes to the curriculum came from those on the centre-right, and has gradually shifted the focus of the revolution away from the Analytical Society to the less-radical influence of Whewell. Thus, while in 1980 Becher argued that the Analytical Society "succeeded" in changing the curriculum, by 1995 he noted that the changes began before the Society's first meeting in 1812 and continued long after its demise around 1817, and that the Society only "set the parameters within which the remodelling of the curriculum would take place".[26]

In foregrounding pedagogy, Becher and Warwick provide a very different account of the influence of the Analytical Society and its members in the adoption of analytical methods and notation into the curriculum of Cambridge. Nonetheless, Woodhouse still largely plays the role of the ultimately ineffective intellectual inspiration of the Society.[27] In this section, I want not only to show how earlier approaches mischaracterized

Woodhouse's influence, but also to show how he plays a crucial role in a pedagogy-centred account. By turning our attention away from Woodhouse's research-oriented *Principles* to his later pedagogical treatises on trigonometry, the calculus of variations, and astronomy, we shall see that he was in fact indispensable for the curricular reformation. Major changes were certainly underway in the 1810s, and those affiliated with the Analytical Society were important to them, yet it was Woodhouse who was in a position to shape their ideas and give their movement legitimacy.

The first meeting of the Analytical Society, according to Philip Enros, took place in Edward Bromhead's rooms in Caius College on 7 May 1812.[28] Since Woodhouse was not only a senior fellow in the small college but also one of those rising in the administration, it is likely that he knew of the proceedings, and the members were certainly aware of his influence. In a Society devoted to new analytical research, two founding members — Babbage and Peacock — credited Woodhouse with introducing the Continental notation to Cambridge.[29] But the connection was not purely inspirational: Bromhead passed on to Woodhouse some of Babbage's work conducted under the auspices of the Analytical Society, and Babbage joined with Woodhouse to support Bromhead's nomination to the Royal Society.[30] By 1813 another member, John Herschel, informed Babbage that rumours were circulating that Woodhouse was the head of this new society of undergraduates.[31] It is no surprise that the author of the *Principles* and the recent analytical texts on trigonometry and the calculus of variations would be linked to like-minded undergraduates meeting in his own college. In addition to the recently-graduated Bromhead, at least one other member of the society, Alexander D'Arblay, was at Caius during the time. The draw of the Analytical Society was great enough for the young Frenchman that D'Arblay's family wrote wishing Woodhouse to steer him in the "Cambridge way" of geometrical methods, so that he could do well in the examinations.[32] The letter suggests that Woodhouse would have at least been aware of the Society and its potential to distract from the examinations.

The Society's publications revealed their debt to Woodhouse. The 1813 *Memoirs* draws heavily on his previous work, both in its historical sketch and in the approach to trigonometry. The trigonometric paper starts, as did Woodhouse's *Trigonometry*, from the algebraic definition of sine and cosine, proceeding analytically to derive other truths.[33] The mathematics was far more advanced than Woodhouse's, however, and was intended as original investigation rather than as a text for students. The three most prominent members of the Society, Peacock, Babbage and Herschel, would publish an 1816 translation of Lacroix's *Elementary treatise on the differential and integral calculus* and four years later a set of examples of the calculus.[34] These students, although united in their desire to reform the curriculum, had different views on the proper role of Continental mathematics; as Peacock increasingly influenced the publications of 1816 and 1820, he marginalized the more mathematically advanced work of Herschel and Babbage. Peacock was the closest of the three to Woodhouse: Peacock's notes to the translation rejected Lacroix's method of limits in favour of the method initiated by Lagrange and developed by Woodhouse in the *Principles*;

Peacock's *Collection of examples* distinguished between arithmetic and algebraic equality in the way Woodhouse had suggested nearly two decades earlier.[35] As Babbage and Herschel became increasingly estranged from the university, it would be the Woodhouse-influenced Peacock who first used Continental notation as moderator of the Tripos in 1817.[36]

Enros's explanation for why the undergraduates were able to affect the curriculum is that the younger generation, unlike Woodhouse, was focused both on the development of mathematics as a research profession and the relationship between mathematics and society.[37] Indeed, Woodhouse did little to further research in advanced analysis and his interests after 1803 remained pedagogical. Babbage and Herschel in particular were conducting advanced research in analytical methods throughout the 1810s, far beyond what Woodhouse ever published.[38] Herschel in fact would complain that Woodhouse's *Physical astronomy* was not advanced enough for his liking.[39] The curriculum, however, could change only by a focus on what undergraduates were actually required to know to do well in the Tripos. In the first decades of the nineteenth century, original investigation was limited to an insignificantly small percentage of students and had little relevance to preparation for the questions in the Tripos. The only meaningful change would be to alter what coaches required their pupils to study for the examination.

In this context, Peacock's use of Continental notation on the Tripos of 1817 was a significant and bold step. Although notation itself is a seemingly minor aspect, Newton's notation was intimately linked with fluxions which were in turn believed to be a part of Newton's broader religious and philosophical framework.[40] Peacock's change, however, was possible only because of the work of Woodhouse. As already noted, Peacock's work with the Analytical Society proved him deeply indebted to Woodhouse, and in 1817 he set at least ten questions which drew directly from the *Trigonometry*, *Calculus of variations*, and *Elementary astronomy*. Woodhouse's books in general were cited over 120 times as aids to understanding the Tripos solutions between 1800 and 1820.[41] Thus, when Peacock set these questions, he knew that students would have had the opportunity to be familiar with the notation and style of questions through Woodhouse's texts. Furthermore, Woodhouse's focus on questions within his texts aligned with the teaching strategies of the coaches of hopeful wranglers.[42] The *Trigonometry* was so widely acknowledged as a 'Senate-House book' that it was studied by students like Airy as preparation for the Tripos even before arrival in Cambridge.[43] At Trinity, Peacock himself furnished Airy with a copy of Woodhouse's *Elementary astronomy* in preparation for the Tripos and the mathematically-challenged Thomas Macaulay complained to his mother that "My classics must be Woodhouse, and my amusements summing an infinite series".[44] Students could safely be set analytical questions because they had been prepared for them by their coaches, largely through Woodhouse's books.

This also explains why Woodhouse himself never required analysis as a moderator of the Tripos, despite his holding that position six times between 1799 and 1808 (an unusually high frequency). Before 1809, there were no widely-read books using analytical ideas or Continental notation at Cambridge. In this conservative environment, increasingly controlled by private preparation for the Tripos, it would have made little sense for Woodhouse to ask analytical questions. Woodhouse's *Trigonometry* filled just that lacuna: instead of deriving trigonometry geometrically, it focused on practically constructing it using purely algebraic methods. Through the *Calculus of variations* and the *Trigonometry*, analysis had been used in a variety of problem-solving contexts, ensuring Peacock's questions could be understood. Of course, not all Peacock's analytical problems were drawn from Woodhouse's works, but they familiarized students with the style and notation. No other book could serve this purpose: Peacock's *Collection of examples* would not appear until 1820, and the Analytical Society's translation of Lacroix sold well but there is little evidence that it was immediately incorporated into Tripos questions.

Within this context of Woodhouse's treatises, Peacock's decision to set questions with foreign notation, although bold, is far less radical. If analytical ideas were really being talked about and debated by the brightest undergraduates as early as 1811, we might expect that previous examiners or examinees would have harnessed the spirit, if not the notation, of the analytical methods. W.W. Rouse Ball suggested that after Woodhouse, answers to the Tripos questions might have begun to look more analytical, even if the questions did not change.[45] There also seems to be some evidence that the questions incorporated analytical ideas before Peacock. Becher noted that Michael Slegg wrote to Babbage soon after the Tripos of 1814 that the questions set by Miles Bland and George Macfarlan that year had introduced the "true faith" of the Analytical Society.[46] Indeed, their questions which required the calculus seemed to be of a higher difficulty than previous years, and solutions might well have been given using analytical-style proofs even if the questions were still in Newton's notation.[47] Furthermore, one question in particular suggested a departure from what was considered a Newtonian approach to the calculus: on the very first day, Bland asked the first and second classes to give an *algebraic* relationship between x and y, given a *fluxional* equation that connected them. Although asking for relationships among variables was common between 1800 and 1820, this was only the second time that the examiner specified an algebraic relationship should be drawn out from a purely fluxional equation. Perhaps significantly, the only other example of such a question was in 1808, set by none other than Woodhouse himself.[48] In the eyes of Slegg and the two undergraduates who described the examination to him, the real transformation in the Tripos started before 1817.

These earlier introductions of analysis might also lead us to conclude that any conservative backlash against Peacock's notational change was less because of the introduction of foreign notation — as Becher notes, it cannot "be explained solely on the basis of ignorance of, or hostility toward, French *mathematics*" — and more because of the linkage of Peacock with the radicals of the Analytical Society.[49] After the popularity of Woodhouse's treatises, and the rise and fall of the Analytical Society, it is no surprise that someone eventually made the change of notation on the examination; the materials and infrastructure were ripe for analytical ideas to be incorporated by hopeful wranglers and their coaches. If the significant changes in undergraduate studies at Cambridge constituted "as much a revolution in pedagogy and personnel as it was in mathematical content", Woodhouse did more than serve as a forefather; he provided the coaches and students with examples of how Continental mathematics could be introduced into traditional mixed mathematics.[50]

Some scholars have played down this later influence of Woodhouse, asserting that he had no intention of making large changes at the university. Becher has suggested that Woodhouse lost his "ferver" as he was promoted and only those with more spirit, less reserve and nothing to lose could change the system; Schaffer echoed that by asserting Woodhouse did not want to undertake a large-scale introduction of analysis because he was too "concerned with institutional proprieties".[51] In this telling, Woodhouse was far more conservative than the later brash undergraduates, and thus it took the younger generation to force the change upon the university. This is supported by a letter from Whewell to Herschel, where he claimed that Woodhouse's *Physical astronomy* of 1818 would become a Senate-House book, especially as Woodhouse "is known to have no liking for the ultra-analysts".[52] Even assuming Whewell was correct in his assessment, one should not conclude that Woodhouse did not want analytical methods to enter the curriculum. I believe that "ultra-analysts" referred to those who promoted advance research in analytics, like Babbage and Herschel, not to those who advocated changing the curriculum. Woodhouse never focused on novel investigation like the younger generation, and his texts were solely concerned with introducing students to properly-applied analysis. Critics of Babbage and Herschel claimed that students were drawn to analysis because it could give answers without requiring any thought; Woodhouse made the same critique against his French sources, and was careful to explain the introduction of analytic methods rather than simply give formulae and rules.[53] Independent research was not a part of undergraduate studies during Woodhouse's lifetime, and the Analytical Society in this sense remained largely an anomaly. Woodhouse never advocated original investigation by students, rather he introduced them to analysis through his texts on astronomy and trigonometry which had become crucial for success on the Tripos. Unlike Babbage and Herschel, Woodhouse focused his energy in the arenas where he could have a meaningful impact upon the curriculum. His success was recognized by the *Edinburgh Review* author who — despite many misgivings about the execution of Woodhouse's 1818 treatise on *Physical astronomy* — concluded that "No man has done so much to improve the studies of Cambridge as Mr Woodhouse".[54]

In assessing his influence, contemporary commentators like the Edinburgh author often pointed to his astronomical work, a part of his œuvre which has been largely neglected in the scholarship. As we shall see, a large part of this neglect is due to the simultaneous decline of Woodhouse's health and the rise of a new generation of English astronomers, especially George Airy. This part of his work, however, played an important role in the changing focus of scientific education at Cambridge. For all the historiographical emphasis on the Analytical Society, and even though Leibniz's differential notation would be consistently used in the Tripos after 1819, the mathematical curriculum would remain quite conservative. What would change significantly at Cambridge, however, was the means of doing astronomy. As the first director of the observatory and the Plumian Professor of Astronomy, Woodhouse played an important role in this transformation. Now we turn to the last fifteen years of Woodhouse's career, and the way in which his move towards astronomy was both a fitting end to his academic work and a mirror of the larger changes in British science at the time.

4. ASTRONOMY AND WOODHOUSE'S MATHEMATICAL LEGACY RE-EXAMINED

When the second edition of Woodhouse's *Trigonometry* came out in 1813, he had already written an elementary text on astronomy, the first of his three publications on the topic between 1812 and 1822. These texts were part of the major transformation of astronomy in Britain between 1810 and 1830.[55] For Woodhouse, astronomy represented the perfection of analytic mathematics, exemplified by the work of Laplace. Woodhouse's 1812 and 1818 volumes on astronomy were intended in large part to replace Vince's *Complete system of astronomy*, issued between 1794 and 1808. Although Woodhouse's review of Vince's first volume in 1798 had nothing but praise for his predecessor, he began to quibble with the second volume three years later. Woodhouse believed Laplace had better explanations of natural phenomena, especially those involving the tides, and a large part of this success was due to the use of analytics rather than synthetics. Vince's synthetic approach was "neither so direct nor so exact as the analytical" and his treatise failed to be "symmetrical" because Vince was forced to mix the two methods together at times to rectify deficiencies in the synthetic method.[56] Woodhouse made an effort to make sure he did not appear as condemning either Vince or the Newtonian tradition, and even noted that Vince could have given Newton more prominence in his historical sketch of astronomy.[57] Vince's system was honourable, but still did not represent the perfection and power of the subject which could be achieved by utilizing the research of the French analytic school of Laplace and Lagrange.

In framing his own project, it is no surprise that Woodhouse wanted to bring Britain in line with the French mathematicians. This was part of a much larger infusion of French scientific research into Britain just beginning at the time. Crosland and Smith have detailed how this transmission of physics from France to Britain occurred from 1800 to 1840. Part of the reason they attribute the high level of development to France was Laplace's reductionist programme, reshaping previously diffuse concepts under one mathematical theory.[58] Although Woodhouse praised Laplace's mathematics, he never expressed a desire to reduce all explanation of natural phenomena to attractive and repulsive forces. Nonetheless, he certainly wanted to harness the explanatory power of the mathematics in Laplace's *Traité de mécanique céleste* and consequently was one of the first involved in the diffusion from France to England.

Woodhouse played an integral role in this transformation, and not simply that of the forefather of the Analytical Society.[59] Rather, as the writer of the Tripos trigonometry and astronomy texts, he began to introduce analytic ideas into popular textbooks used by Cambridge students. The importance of carefully introducing new concepts into Cambridge mixed mathematics should not be underestimated. Because of the conservative nature of the curriculum, mathematical explanations had to reach a level of 'certainty' before their acceptance; witness the ignorance of Coulomb's 1780s texts until Poisson's mathematical reformation brought the theory in line with observation.[60] Astronomy was ideal for Woodhouse because it was for him the example of a complete and perfected theory. He promoted analytic methods only when they were developed enough to be of utility for the training of students, never as tentative avenues for new inquiry. Woodhouse thus introduced the more elementary aspects of Laplace's astronomical texts in 1818 without changing the essential nature of the Cambridge curriculum; his success is evinced by the fact that although Whewell never approved of the Laplacian programme generally, he came to appreciate Laplace's astronomical work.[61]

This point is unfortunately downplayed in Crosland and Smith's article. They call Woodhouse's *Physical astronomy* of 1818 "rather obscure" and immediately focus on Whewell's 1819 and 1823 treatises on mechanics and dynamics as well as Airy's work in the 1820s.[62] This is a surprising move, not only as Woodhouse was the Lucasian and Plumian Professor in the 1820s — and the first director of the observatory — but also because it is certain that Airy studied and learned from Woodhouse's astronomical treatises and that both Airy and Whewell (independently) called Woodhouse's *Physical astronomy* an "epoch" in Cambridge mathematics. Whewell predicted that it was destined to become a Senate-House book despite its use of 'new' mathematics, and consequently questions in the style of Newton would soon become obsolete.[63] It not only elevated physical astronomy to the status of a deductive science but also served as the model for Airy and Herschel's later astronomical work.[64] Whewell, Herschel and Airy would have a greater impact over time upon the study of astronomy and mathematics at Cambridge, but Woodhouse deserves the credit for ensuring that Laplacian astronomical ideas entered the Cambridge curriculum with greater ease than almost any other subject of French science. No doubt this was partially due to his portraying Lagrange and Laplace as Newton's "successors" in astronomy; he intended their texts to be read as the natural conclusion of the investigations Newton instigated.[65] Far from passively translating treatises, Woodhouse actively adapted French mathematics into the established Cambridge curriculum, synthesizing relevant aspects of each style.

Woodhouse's three treatises spanned a decade and two editions. The first edition of his *Elementary astronomy* had two volumes, the first issued in 1812 and the second in 1818 with the subtitle *Physical astronomy*. The first volume of the second edition, printed in 1822, was long enough to justify two parts, and the second volume was apparently never completed. All three are intended to explain rather than extend the subject and exclude those aspects of theory and practice that were not of "practical utility".[66] Taking them together, we see a bi-directional learning process; the two editions of *Elementary astronomy* build up from the first observations of the sky, to the instruments we would use to observe the sky more rigidly, to the mathematics that explains what we observe. The *Physical astronomy* on the other hand, takes the perspective that we start with mathematics and can deduce and predict physical phenomena and deviations. In this sense, the treatises united the British and French perspectives: they showed the student how to build up theory and explanation from observation and how to predict observations from mathematical equations.

Part of what allowed him to unite these methodologies was his sense that astronomy was mathematically complete. He noted that we could deduce 500 equations to describe solutions in practical astronomy "and compute coefficients so minute, that observations made for centuries, with instruments more perfect than what are now used, will not be able to verify.... In order to know how far it is useful to extend our calculations, we must refer to observation".[67] By 1822, the field was nearly perfected, and "Having reached a kind of *maximum* state of excellence, its changes are minute and must continue to be so".[68] The mathematics was complete and stable, leaving only observations, which would reflexively provide the limit of how far we needed to deduce coefficients mathematically. He had described this transformation as early as 1800, where astronomy, in the hands of its practitioners from Newton to Laplace, had moved from observation to the laws of motion to the principle of gravitation and from here could descend from these principles to the "complete explication of all the heavenly phænomena, even in their minutest details". All that is left is "to make numerous observations on our own system".[69]

This portrayal of completeness had two major consequences for the study of astronomy. First, Woodhouse's writings became focused on the student in an attempt to show him how to operate the machinery as well as learn the mathematical explanations underlying the observations. In this regard, in his first edition of the *Elementary astronomy* Woodhouse lamented the lack of an observatory at Cambridge because it would have been useful for students starting on the subject. By 1822, he knew that an observatory was not far off, and accordingly wrote an additional introductory note.[70] Here, he laid out the three goals for the observatory: to make the best observations possible, to make as many as possible, and to publish all findings annually. These in turn required the best instruments, training of men skilled at using the instruments, and participation in the broader astronomical community.[71] The treatise was intended to meet these requirements, explaining the instruments and training new observers, rather than advancing the field. Similarly, *Physical astronomy* presented the mathematics necessary for understanding astronomy in a way amenable to Tripos preparation.[72] It is unlikely that Cambridge students themselves would be physically participating in the observatory, but Woodhouse ensured students would have to know how to use the instruments before they could be said to understand astronomy.

In writing treatises that would simultaneously be conservative enough to be of use in the Tripos and also prepare students for the new methods of astronomy, Woodhouse moved away from French analysis even as he introduced it into the curriculum. Firmly rooted in the Cambridge system after spending over two decades in the path from wrangler to fellow to professor, Woodhouse wrote treatises useful for undergraduates focused on the examination but also showing the way forward in 'complete' fields like astronomy. Although his relative conservatism could be dismissed as a concession to university pressure, he set an example for how powerful new mathematics could be introduced without changing the traditional Cambridge focus on mixed mathematics.[73] Had Woodhouse written treatises only on advanced analysis, it is not likely that he would have had an impact on the Cambridge curriculum.

Second, the shift of astronomy to the observatory marked an important transition not just for Cambridge mathematics but for the field generally. Mathematics itself was now required for 'detecting' planetary deviations and their causes; that is, the mathematics explained all celestial motion.[74] With the theory in place, the only remaining way to advance the field was to increase the number and precision of observations to complement the mathematics. Thus, observatories would come to the forefront of university astronomy. Observatories, Woodhouse noted in the preface to the second edition of his *Elementary astronomy*, are intended to be used neither to increase the fame of universities nor mainly to correct results from abroad, but rather "to enlarge the boundaries of Science".[75] With perfected mathematics, science was dependent upon the manual labour of observation for its development.

To this end, between 1825 and 1827 Woodhouse published three articles in the *Transactions of the Royal Society* describing the observatory's only instrument, a transit telescope, and then investigating a discrepancy in observation.[76] He found the readings to be generally unreliable, and in 1827 described a series of experiments to attempt to account for such inaccuracies. All three papers focus entirely on the instruments and detailed descriptions of his observations and methodology. Instead of the mathematical argument and analysis prevalent in his *Transactions* articles from 1800 to 1804, the focus is now entirely on the precision of measurement. However, that is not to say that he was not interested in instrumentation earlier. Even as a recent graduate, he was focusing on the impact and importance of instrumental error. He noted that although it should be sharply differentiated from mathematical mistakes, instrumental error could not be separated from human error. The two were one and the same and this naturally resulted in a focus on the proper use of the instruments within the observatory.[77]

Woodhouse was never able to develop the Cambridge observatory to the extent that he would have desired, as he was plagued with personal troubles from the time he was appointed its first director. Having secured the relatively lucrative Plumian Professorship in 1822, he left Caius, where he had spent the last three decades, to marry Harriet Wilkens in Paris.[78] From this point on, his life appears to have rapidly declined. Woodhouse was in poor health by 1824 and his wife was to die in April 1826, followed by Woodhouse himself in December 1827. Woodhouse was not able to muster much more than the *Transactions* articles after his appointment in 1824.

Although he was not able to develop the Cambridge observatory into the knowledge-producing machine he envisaged, Woodhouse's work on astronomy was seen as a success by contemporary critics. John Brinkley's review of the *Physical astronomy* noted that it showed analytics could be used to train the mind effectively, countering the charges that only synthetics belonged in a university setting.[79]

Similarly, Baden Powell's review praised the focus on careful parsing of definitions for pedagogical purposes. Powell deferred to Woodhouse's own judgement that astronomy had reached a state of perfection and consequently asserted that it would be useful for students actually to know what it was like to be in an observatory.[80] This point was picked up by De Morgan, who in the *Penny cyclopaedia* article on Woodhouse extolled at length the virtues of his work on astronomy:

> The first volume [of *Elementary astronomy*] still remains perhaps the most remarkable work on astronomy of its century. This distinction it owes to the manner in which Woodhouse makes the reader feel that he is in the very observatory itself. The methods are as perfect as if they had been directions to a computer, a quality which writers who have to explain those methods mathematically frequently do not give them; the examples seem as if they were real ones, as if some astronomer had had to put down the actual figures, and the very observations which are cited are made to smell of the instruments which gave them.... The secret was, that the author was an expert practical astronomer, as well as an original thinker on first principles, who was able to change places with the student in an unusual degree.[81]

De Morgan nicely crystallizes the two major facets of Woodhouse's practical astronomy: the focus on the student and the importance of actual experience in the observatory.

The treatises were also praised for their integration of analytic ideas into the field perhaps most influenced by Newton's legacy in Britain. The anonymous author reviewing Woodhouse's *Physical astronomy* in the *Edinburgh Review* predicted that soon the "principles of Analysis will form a larger portion of the studies of [Cambridge]; — and we are sure nothing is so likely to hasten that period, as the publication of such mathematical works as that before us".[82] The evaluation that it was the incorporation of analytics with astronomy that truly brought about a kind of revolution in the studies of Cambridge was supported by one of the most influential of Cambridge men, William Whewell. In a letter to his friend H. J. Rose, Whewell complained of the outdated nature of most of the treatises available, but expressed hope that Woodhouse's treatise would change the situation. Whewell wrote that:

> There is comfort in being able to do anything in the way of reformation. Woodhouse has been doing something by publishing a physical astronomy. It is like his other books — a new mathematical currency which was much wanted, executed in no very neat manner but still good metal — so that at worst it may be melted down and coined over again. It will I have no doubt make its way into the Senate House — especially as we have Gwatkin and Peacock for moderators.[83]

In depicting celestial astronomy as a mathematically complete field ripe for reforming Cambridge mixed mathematics, Woodhouse laid the groundwork for it, alongside optics, to become one of Whewell's "permanent" sciences. Unlike "progressive" sciences, these were appropriate for general undergraduate education, and in this letter, Whewell credited Woodhouse with shaping foreign developments into material useful for the Tripos.[84]

Whewell, although initially engaged in the push for curricular change, published a treatise on mechanics in 1819 that had few elements of reform. Taking a synthetic approach, it was largely geometric and would be the start of what would become a consistent effort of his to maintain the traditional curriculum.[85] Starting again from intuitions about motion rather than abstract mathematical ideas, Whewell effectively reduced Laplace's *Mécanique céleste* to a collection of footnotes. Both Whewell and Woodhouse portrayed current astronomical developments as part of the Newtonian legacy, but Whewell's treatise was notably more conservative than Woodhouse's. This similarity and difference contributed to the demise of Woodhouse's legacy, for over time Whewell promoted ever-more conservative visions for mathematical education and Woodhouse's more mathematically-sophisticated astronomical texts appeared increasingly inconvenient for students preparing for an examination in Whewell's style. In this movement away from Woodhouse, Whewell saw an ally in his younger protégé, George Airy.

Airy entered Whewell's Trinity College in 1819, and graduated senior wrangler and first Smith's prizeman — with Woodhouse as one of his examiners — in 1823. As an undergraduate, Airy learned astronomy from Woodhouse's treatise. When the second edition was published in 1822, Airy annotated the first with the appropriate corrections.[86] His interest and ability in astronomy were quickly evident and within thirteen years of graduation, he had been awarded the gold medal of the Astronomical Society, appointed successively to the Lucasian and Plumian Professorships, asked to head the Cambridge Observatory, invited to join the Royal Society and appointed Astronomer Royal. Having not only learned astronomy from Woodhouse's treatises, but also having followed him to the Plumian Chair and observatory, one might expect Airy to have a certain degree of reverence for the elder professor. Such was not the case.

Airy was quick to remove Woodhouse's work from the records, and is at least partially responsible for the lack of information that we have about Woodhouse. Although we can only speculate as to the relationship between Airy and Woodhouse, it is clear that Airy recognised his own astronomical talents and was eager to advance in scientific circles. Whether intentionally or not, the net effect of Airy's advance was the virtual elimination of Woodhouse from the historiography of nineteenth-century astronomy. Airy was just coming into his own about the time Woodhouse married and began having health problems. Hearing that Woodhouse had fallen seriously ill in 1826, Airy's thoughts turned to the opportunity this represented for him, and as a political move to ensure his election as Plumian Professor, he succeeded in being named one of those temporarily in charge of the observatory.[87] A few months later, Airy matter-of-factly wrote to his uncle regarding the death of Woodhouse, who he dismissed as suffering from "melancholy derangement", and as the new owner of the estate given to the observatory head, Airy began assessing the worth of his future home.[88] The ever cost-conscious Airy, confident of his coming appointment, had even begun to evaluate Woodhouse's furniture before the election, and decided he would auction it off, which he did less than a week after he assumed office.[89] Believing his newly inherited home to be more trouble than it was worth, he tried to get the late-professor's estate to pay for as many repairs as possible.[90] No record remains of what exactly Airy chose to do with Woodhouse's papers and manuscripts (if any) in his home. There probably was not that much of value for Airy, with Woodhouse's abandoning his college fellowship only a few years earlier. Furthermore, the only remaining family of Woodhouse — his brothers and infant son — apparently had no interest in his possessions. The professor's material record was soon erased.

In assuming his new role as one of the spokesmen for English astronomy, Airy chose to downplay, if not ignore, Woodhouse's contribution to the science. The first edition of his *Mathematical tracts* extended Woodhouse's work on the lunar theory, but with a more Whewellian approach; yet, Airy made it clear that it was "not intended, in the slightest degree, to supersede the Treatise of Professor Woodhouse".[91] By the second edition five years later, with Woodhouse dead, Airy no longer mentioned his predecessor in the preface, and instead shifted further to the geometric approach. Airy believed certainty rested in the geometrical, whilst the mechanical approach was "far from certain".[92] Airy and Whewell's approaches reinforced each other, and collectively the effect was to push Woodhouse's works to the periphery of student experience, making them seem increasingly less convenient for examination preparation.[93]

Airy felt confident enough in assuming his new role within British astronomy that he surprisingly failed even to mention Woodhouse's work in his 1833 "Report on the Progress of Astronomy during the Present Century". Furthermore, he claimed that the only useful astronomical work in Britain had taken place after 1827, the year of Woodhouse's death and the year Airy began work in the Cambridge Observatory. The omission is even more glaring when one considers the intellectual debt Airy owed to Woodhouse. Although Woodhouse's *Physical astronomy* was privately called an "epoch" in Airy's mathematical education, publicly he would not even mention it.[94] Yet, in the "Report", his focus was notably similar to that which Woodhouse espoused in his astronomical writings. Airy believed that Britain should promote the connection between "physical theory and practical observation" which was common on the Continent.[95] This was precisely the plan elucidated by Woodhouse in his 1822 preface, which Airy almost certainly read. At any rate, because of Woodhouse's poor health, Airy would accomplish far more during his tenure as head of the observatory, and would carry out this scheme of practical astronomy by focusing on the daily operation of the observatory. Just as Woodhouse wrote to the Royal Society concerning the accuracy of the observatory's instrument, Airy would focus his work on the role of the practical in doing astronomy. Even before Airy took his first degree he was working on perfecting the instruments of the observatory, whose operation he most likely learned from Woodhouse himself.[96] The new aim of the astronomical sciences was to make good observations, make many of them, communicate them to others, and to focus on the training of labourers and the operation of the observatory.[97] Woodhouse had been the first to design and specify this plan, but Airy would be the first to implement it. Although it would be too speculative to say that Airy intentionally downplayed Woodhouse to take full credit for the implementation of observatory management, his choice not to emphasize Woodhouse in his writings caused Woodhouse's contributions to astronomy and astronomy pedagogy to be largely ignored.

Woodhouse's important astronomical works not only represent the *dénouement* of his career, but also mirror the larger changes in the sciences at Cambridge. When Woodhouse took his degree in 1795, the focus of the scientific curriculum was on defending and expounding Newton's theories. Now, three decades later, with the massive influx of Continental scientific treatises, the landscape of knowledge was entirely different at Cambridge, even if students were still engaged in the preparation for examinations. In astronomy, which was once solely a geometric study of Newtonian forces, the research focus was on instrumentation and operation whilst students studied (appropriately edited versions of) Laplace. More research needs to be done on the mechanisms underlying this transformation in astronomy and its relationship to the mathematics of the period. For instance, Woodhouse's early mathematical work could be examined in light of his French sources and his later work in reference to other astronomers such as John Herschel.[98] At a minimum, by tactfully introducing analysis in 1803, then gradually convincing the dons of its usefulness within trigonometry and astronomy by writing Tripos-appropriate treatises on the subjects, Woodhouse was integral to the transformation of astronomy at Cambridge.

CONCLUSION

Airy's rapid ascent within the astronomical world ensured Woodhouse would fall into relative obscurity. Woodhouse's legacy, preserved by his being portrayed as a forefather to the more dominant personalities who would come after him, was also confined by those same personalities. The account of Woodhouse as an ineffective figurehead who needed the likes of Herschel, Babbage, Peacock and Airy to carry out his vision has largely remained with us until the present day. No doubt it was aided by an historiography that put more focus on independent investigation — to which these latter figures were central — rather than on the actual facets of the Cambridge curriculum. Woodhouse himself might have hindered his long-term reputation through his own shyness; certainly later figures like Airy, Whewell and Babbage suffered from no such reserve.[99] Although there is no need for a hagiographic restoration of Woodhouse, reassessing his influence allows us to see how a man with progressive ideas could attempt to implement them in an extraordinarily conservative environment. His influence was most strongly felt in two ways. First, he laid the groundwork for the introduction of Continental notation and analytical methods, demonstrating to later generations that it was possible to incorporate new ideas from abroad without abandoning the traditional curriculum as a whole. His *Principles* assured Cantabridgians that analysis could be grounded properly and also that it was consistent with the revered fluxions of Newton. In one respect, his calculus work was so influential that when Cauchy established a new era in French mathematics with a 'formal' definition of limits, it would initially be rejected by Britons who were still devoted to the system of Lagrange, first elucidated by Woodhouse decades earlier.[100] More significantly, his later texts became essential for coaches and students and ensured that analysis would become a part of the knowledge required to do well in the Tripos. He was able to do this not by promoting or publishing independent research, but rather by framing powerful new mathematical methods as appropriate for the examination of undergraduates.

Second, his influence is evident in astronomy. The transition here had a dual nature: as Woodhouse introduced the power of French mathematics into Britain, observatories needed to take these analytical tools on board; conversely, Woodhouse showed that because the mathematics underlying celestial mechanics was complete, astronomers needed to turn to the practical aspects of the observatory to advance the field. Although astronomy was the dominant focus of his intellectual output, it has played a minor role in the historiography primarily because of Airy's presence for much of the nineteenth century. Woodhouse laid out the principles and groundwork for a new astronomical programme, but it would be Airy who would implement them.

Despite the important changes in astronomy and mathematical studies at Cambridge, it was not an entirely radical era. Indeed, analysis was generally introduced without much upheaval — the Tripos increased in importance over the period and mathematics largely remained subservient to natural philosophy. As Whewell rose in prominence, he "restored Cambridge tradition by reforming it", co-opting analysis for traditional mixed mathematics and segregating original research.[101] If anything, this story alerts us to the danger of using our standard of mathematical excellence — original research — to explain historical changes. In a culture of preparing 'gentlemen', where mathematics was studied seriously by a small number of students and seen largely as a means to an end, changes would not be brought about by those intent on groundbreaking investigation alone. It would take men with progressive ideas and an understanding of the traditional curriculum, not those looking for a revolution, to change how mathematics was studied and how astronomy ought to be done. To the extent that there was a chasm between the Cambridge of 1795 and that of 1825, Woodhouse remained the only figure who truly bridged the world of Vince and Wood, with whom he began his work, to that of Airy, Peacock and Whewell, who would be the key figures of the next decades. By focusing on the bridge instead of the chasm we see how apparently slow and small alterations were at least as effective at changing the curriculum of early nineteenth-century Cambridge as any novel mathematical investigation.

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REFERENCES

1. This assessment is found in nearly all general histories of mathematics, but even in writings of historians sympathetic to the period, e.g. J. M. Dubbey, *The mathematical work of Charles Babbage* (Cambridge, 1978), 10 and M. Fisch, "'The emergency which has arrived': The problematic history of nineteenth century British algebra — a programmatic outline", *The British journal for the history of science*, xxvii (1994), 247–76, p. 250. Recently, N. Guicciardini in "Dot-age: Newton's mathematical legacy in the eighteenth century", *Early science and medicine*, ix (2004), 218–56 and *The development of Newtonian calculus in Britain 1700–1800* (Cambridge, 1989) has forwarded a more nuanced and complex view of the British mathematical tradition.
2. His legacy in these areas has been well documented. For his influence on logic and algebra (especially on Augustus De Morgan), see M. Panteki, "The mathematical background of George Boole's Mathematical Analysis of Logic (1847)", in *A Boole anthology: Recent and classical studies in the logic of George Boole*, ed. by J. Gasser (Dordrecht, 2000), and *idem*, "French 'logique' and British 'logic': On the origins of Augustus De Morgan's early logical enquiries, 1805–1835", *Historia mathematica*, xxx (2003), 278–340; D. Sherry, "The logic of impossible quantities", *Studies in history and philosophy of science*, xxii (1991), 37–62; H. Pycior, "George Peacock and the British origins of symbolic algebra", *Historia mathematica*, viii (1981), 23–45; H. Pycior, "Internalism, externalism and beyond: 19th century British algebra", *Historia mathematica*, xi (1984), 424–41; J. L. Richards, "The art and science of British algebra: A study in the perception of mathematical truth", *Historia mathematica*, vii (1980), 343–65; H. Becher, "Woodhouse, Babbage, Peacock, and modern algebra", *Historia mathematica*, vii (1980), 389–400; and J. M. Dubbey, "Babbage, Peacock, and modern algebra", *Historia mathematica*, iv (1977), 295–302. For the later influence on analysis, see E. Koppelman, "The calculus of operations and the rise of abstract algebra", *Archive for the history of exact sciences*, viii (1971), 155–242; P. Enros, "The Analytical Society: Mathematics at Cambridge University in the early 19th century", Ph.D. dissertation, University of Toronto, 1979; *idem*, "Cambridge University and the adaptation of analytics in the early nineteenth-century England", in *Social history of nineteenth century mathematics*, ed. by Herbert Mehrtens, H. J. M. Bos and Ivo Schneider (Boston, 1981), 135–47; *idem*, "Analytical Society (1812–1813): Precursor of the renewal of Cambridge mathematics", *Historia mathematica*, x (1983), 24–47; M. Panteki, "William Wallace and the introduction of Continental calculus to Britain", *Historia mathematica*, xiv (1987), 119–32; J. M. Dubbey, "Introduction of the differential notation to Great Britain", *Annals of science*, xix (1963), 37–48; and *idem*, "Robert Woodhouse and the establishment of a mathematical basis for the calculus", M.Sc. dissertation, University of London, 1964. For his brief tenure as Lucasian professor, see S. Schaffer, "Paper and brass: The Lucasian Professorship 1820–39," in *A history of Cambridge University's Lucasian Professors of Mathematics*, ed. by K. C. Knox and R. Noakes (Cambridge, 2003), 241–93.
3. There is little extant biographical information, mainly located in J. Venn, *Biographical history of Gonville and Caius College, 1349–1897: containing a list of all known members of the college from the foundation to the present time, with biographical notes* (Cambridge, 1897), 119–20, and

A. De Morgan, "Robert Woodhouse", *Penny cyclopaedia*, xxvii (1843), 526–7. George Morgan ardently supported the revolution and was likely an early source of French mathematics for Woodhouse. See D. O. Thomas, "Morgan, George Cadogan", in *Oxford dictionary of national biography* (Oxford, 2004). We know Woodhouse was Morgan's pupil from a letter of Morgan's uncle, Richard Price. See W. B. Peach and D. O. Thomas, *Correspondence of Richard Price*, iii (Durham, 1994), 178. I am indebted to Simon Schaffer for this point.

4. Enros, in "The Analytical Society" (ref. 2) references B. C. Nangle, *The Monthly Review, 2nd series, 1790–1815; indexes of contributors and articles* (Oxford, 1955), which I also used to determine authorship of *Monthly Review* articles.
5. By culminating the story in Lagrange, Woodhouse not only dismisses Maclaurin and other fluxionists but also Britons such as Landen and Waring who used algebraic techniques yet in Woodhouse's view remained vulnerable to Berkeley's criticisms. Berkeley argued that the method of fluxions was not geometrically rigorous, in part because it required a notion of infinitesimals, which Berkeley did not believe existed.
6. R. Woodhouse, *The principles of analytical calculation* (Cambridge, 1803), p. xxv. Richards also makes a useful distinction between generalization and abstraction in Woodhouse's work: J. L. Richards, "Rigor and clarity: Foundations of mathematics in France and England, 1800–1840", *Science in context*, iv (1991), 279–319, pp. 311–13. See Dubbey, *Robert Woodhouse and the establishment of a mathematical basis for the calculus* (ref. 2) for a mathematical analysis of the text. The idea that Newton relied primarily on geometry is a late eighteenth-century construct, but as this was generally how Woodhouse and other Cambridge men interpreted Newton, I will continue to associate the two.
7. This was hardly a novel theory and was deeply related to Enlightenment philosophy. See Sherry, "The logic of impossible quantities" (ref. 2), 47–54.
8. Woodhouse, *Principles* (ref. 6), p. ii.
9. See W. W. Rouse Ball, *The origin and history of the Mathematical Tripos* (Cambridge, 1880), and J. Gascoigne, "Mathematics and meritocracy: The emergence of the Cambridge Mathematical Tripos", *Social studies of science*, xiv (1984), 547–84 regarding the Mathematical Tripos.
10. A. Warwick, *Masters of theory: Cambridge and the rise of mathematical physics* (Chicago, 2003), 89–94. The term 'coach' here is anachronistic as it became common only after Woodhouse's death; nonetheless it referred to the same practice of private tutoring.
11. Of course it was not completely ignored; for some of the response, see Enros, "The Analytical Society" (ref. 2), 88–89. Historians have shown how Woodhouse's arguments in the *Principles*, largely developed in his *Monthly Review* articles, proved suggestive and influential for later developments in algebra and analysis (see ref. 1).
12. C. Brooke, *History of Gonville and Caius College* (Woodbridge, 1985), 186.
13. See for example, R. Woodhouse, "Review of Vince's Complete System of Astronomy", *Monthly Review*, xxvii (1798), 121–31, p. 131.
14. R. Woodhouse, *Treatise on isoperimetrical problems and the calculus of variations* (Cambridge, 1810).
15. G. Peacock, "Report on the recent progress and present state of certain branches of analysis", *Third report of the British Association for the Advancement of Science* (1834), 185–352, p. 295.
16. R. Woodhouse, *Treatise on plane and spherical trigonometry*, 1st edn (Cambridge, 1809), pp. vii, 14, 99.
17. *Ibid*., 93.
18. *Ibid.*, 117ff.
19. *Ibid*., 180.
20. Peacock, "Report" (ref. 15), 296.

21. Whewell letter to Herschel on 1 November 1818, in I. Todhunter, *William Whewell, D.D., Master of Trinity College, Cambridge: An account of his writings; with selections from his literary and scientific correspondence*, ii (London, 1876), 30.
22. As a more senior fellow than Woodhouse at Caius, Vince's support was most likely needed to be appointed a senior fellow and was likely given as he had already supported Woodhouse's bid to join the Royal Society in 1802; see Royal Society Archives, EC/1802/08.
23. R. Woodhouse, *An elementary treatise on astronomy: Physical astronomy*, 1st edn, ii (Cambridge, 1818); R. Woodhouse, "Review of Lagrange's Leçons sur le Calcul des Fonctions", *Monthly review*, xlix (1806), 486–98, p. 489.
24. See Warwick, *Masters of theory* (ref. 10), 49–113.
25. Richards, "Rigor and clarity" (ref. 6), 307–9.
26. Becher, "Woodhouse, Babbage, Peacock, and modern algebra" (ref. 2), 397; H. Becher, "Radicals, Whigs, and conservatives: The middle and lower classes in the analytical revolution at Cambridge in the age of aristocracy", *The British journal for the history of science*, xxviii (1995), 405–26, p. 406.
27. Many historians have focused on the 'success' of the Analytical Society and/or the failure of Woodhouse in this context: see W. W. Rouse Ball, *A history of the study of mathematics at Cambridge* (Cambridge, 1889), 120–2; Enros, "The Analytical Society" (ref. 2), 215; C. Smith and M. N. Wise, *Energy and empire: A biographical study of Lord Kelvin* (Cambridge, 1989), 151; M. V. Wilkes, "Herschel, Peacock, Babbage, and the development of the Cambridge curriculum", *Notes and records of the Royal Society*, xliv (1990), 205–19, p. 207; Fisch, "The emergency which has arrived" (ref. 1), 247; and W. Ashworth, "Memory, efficiency, and symbolic analysis: Charles Babbage, John Herschel, and the industrial mind", *Isis*, lxxxvii (1996), 629–53, pp. 632–6.
28. Enros, "The Analytical Society" (ref. 2), 103. S. Schweber (ed.), *Aspects of the life and thought of Sir John Frederick Herschel*, i (New York, 1981), 57–59 has earlier dates for the first meetings, but on either account they were held in Bromhead's rooms.
29. Peacock, "Report" (ref. 15), 295; C. Babbage, *Passages from the life of a philosopher* (London, 1864), 26.
30. Dubbey, *The mathematical work of Charles Babbage* (ref. 1), 62; Royal Society archives, EC1816/16. Bromhead also credits Woodhouse with introducing students to Lagrange and other foreign expositors of the calculus, see E. Bromhead, "Differential calculus", *Supplement to the Encyclopedia Britannica*, iii (1824), 568–72, p. 568.
31. Enros, "The Analytical Society" (ref. 2), 158.
32. Letter of 1 January 1814, quoted in *ibid*., 119–20.
33. A. Society, *Memoirs* (Cambridge, 1813), 33.
34. S. Lacroix, *Elementary treatise on the differential and integral calculus*, transl. by Charles Babbage, John Herschel, and George Peacock (Cambridge, 1816); G. Peacock, *A collection of examples of the applications of the differential and integral calculus* (Cambridge, 1820).
35. Richards, "Rigor and clarity" (ref. 6), 311–13, and Becher, "Woodhouse, Babbage, Peacock, and modern algebra" (ref. 2), 396.
36. As for the Society, there is some disagreement regarding the formal concluding dates; see M. Fisch, "The making of Peacock's Treatise on Algebra: A case of creative indecision", *Archives for the history of exact science*, liv (1999), 137–79, p. 137.
37. See Enros, "The Analytical Society" (ref. 2), 102, 215. Fisch, in "Peacock's Treatise" (ref. 36), emphasizes Peacock's pedagogical focus, although he was increasingly distanced from the other members and this focus should be more associated with him than with the Analytical Society.
38. Enros, "The Analytical Society" (ref. 2), 179–200.
39. J. Herschel, "Review of Somerville's Mechanism of the Heavens", *Quarterly Review*, xlvii (1832),

537–59, p. 547.

40. K. C. Knox, "The negative side of nothing: Edward Waring, Isaac Milner and Newtonian values," in *From Newton to Hawking*, ed. by Knox and Noakes (ref. 2), 205–40, p. 236.
41. See the index to J. M. F. Wright, *Solutions of the Cambridge problems: From 1800 to 1820* (London, 1825), also cited in Becher, "Woodhouse, Babbage, Peacock, and modern algebra" (ref. 2), 393. Of course, Wright was not listing the books that were useful for past examinations, but rather those that contemporary (1825) students would find useful for answering the older questions. Nonetheless, it indicates how pervasive Woodhouse's book had become by the 1820s as preparation for the Tripos.
42. G. Airy, *Autobiography of Sir George Biddell Airy*, ed. by Wilfred Airy (Cambridge, 1896), 33.
43. *Ibid*., 20. 'Senate-House' referred to the location of the Tripos examination.
44. *Ibid*., 26; Macaulay quoted in S. F. Cannon, *Science in culture: The early Victorian period* (New York, 1978), 31.
45. Rouse Ball, *Mathematics at Cambridge* (ref. 27), 119–20.
46. See Becher, "Radicals, Whigs, conservatives" (ref. 26), 413, who cites Babbage Correspondence, fol. 26, letter of 4 February 1814.
47. Anonymous, *Cambridge problems: being a collection of the printed questions proposed to the candidates for the degree of bachelor of arts at the general examinations from 1801 to 1820 inclusive* (Cambridge, 1821), 268–75.
48. Although this might be making too much of the wording of the question, it seems significant that these were the only times algebra and the calculus were explicitly connected in a question. For the problems, see *ibid*., 145, 265.
49. Becher, "Radicals, Whigs, conservatives" (ref. 26), 414.
50. Warwick, *Masters of theory* (ref. 10), 51.
51. H. Becher, "William Whewell and Cambridge mathematics", *Historical studies in the physical sciences*, xi (1980), 1–48, pp. 9–10; Schaffer, "Paper and brass" (ref. 2), 261. See also H. Becher, "Woodhouse, Robert," in *Oxford dictionary of national biography* (ref. 3).
52. In Todhunter, *William Whewell* (ref. 21), 30.
53. A typical critic was A. Browne, *A short view of the first principles of the differential calculus* (Cambridge, 1824), p. ix; Woodhouse made this same point in R. Woodhouse, "Review of Lacroix's Traité des Differences et des Series", *Monthly review*, xxxvi (1801), 498–501, p. 500 and R. Woodhouse, "Review of Bonnycastle's Treatise on Plane and Spherical Trigonometry", *Monthly Review*, liii (1807), 279–85, p. 285. This criticism was closely related to the debate over whether students would be turned into mindless calculating machines through the new analysis. See Schaffer, "Paper and brass" (ref. 2); W. Ashworth, "The calculating eye: Baily, Herschel, Babbage and the business of astronomy", *The British journal for the history of science*, xxvii (1994), 409–41; *idem*, "Memory, efficiency, and symbolic analysis" (ref. 27); and I. Grattan-Guinness, "Charles Babbage as an algorithmic thinker", *IEEE Annals of the history of computing*, xiv/3 (1992), 34–48.
54. Anonymous, "Review of Woodhouse's Physical Astronomy", *Edinburgh review*, xxxi (1819), 375–94, p. 394, likely authored by William Brougham.
55. M. Crosland and C. Smith, "Transmission of physics from France to Britain: 1800–1840", *Historical studies in the physical sciences*, ix (1978), 1–61, p. 11.
56. R. Woodhouse, "Review of Vince's Complete System of Astronomy, vol. 2", *Monthly Review*, xxxv (1801), 72–82, p. 82.
57. *Ibid.*, 80.
58. Crosland and Smith, "Transmission of physics" (ref. 55), 5–7.
59. Certainly others were interested in the promotion of Continental mathematics, and these are well

highlighted by Crosland and Smith and include Playfair in Scotland and Lloyd in Ireland.

60. Crosland and Smith, "Transmission of physics" (ref. 55), 19–20.
61. *Ibid*., 51–56.
62. *Ibid*., 13.
63. Airy owned and annotated copies of vol. i of the 1st edn of R. Woodhouse, *An elementary treatise on astronomy* (Cambridge, 1812), and of Woodhouse, *Physical astronomy* (ref. 23). He made appropriate changes when the new edition of Woodhouse was printed in 1822. Airy, *Autobiography* (ref. 42), 29–30; Whewell, letter to Herschel in Todhunter, *William Whewell* (ref. 21), 30. Woodhouse's *Physical astronomy* was the first to incorporate Laplace and would be almost the only complete treatise on the subject for two decades more. See Panteki, "French 'logique'" (ref. 2), 300.
64. Schweber (ed.), *Herschel* (ref. 28), 64. Woodhouse's influence upon Airy is discussed later in this section.
65. Woodhouse, *Physical astronomy* (ref. 23), p. lvii.
66. Woodhouse, *Elementary astronomy*, 1st edn (ref. 63), p. xiv. Although the title page of R. Woodhouse, *An elementary treatise on astronomy*, 2nd edn (Cambridge, 1822) indicates a publishing date of 1821, the preface was not written until 1822.
67. Woodhouse, *Physical astronomy* (ref. 23), p. xiii.
68. Woodhouse, *Elementary astronomy*, 2nd edn (ref. 66), pp. xvii–xviii.
69. R. Woodhouse, "Review of Laplace's Traité de Mécanique Céleste, part 1", *Monthly review*, xxxi (1800), 493–505, p. 472; *idem*, "Review of Laplace's Traité de Mécanique Céleste, part 2", *Monthly review*, xxxii (1800), 478–85, p. 484.
70. As a continued demonstration of the link between the younger generation and Woodhouse, Peacock was influential in securing the observatory of which Woodhouse would become the first supervisor.
71. Woodhouse, *Elementary astronomy*, 2nd edn (ref. 66), pp. xix–xxii.
72. For instance, the method of the variation of constants presented by Woodhouse made its way repeatedly into problems. See Panteki, "French 'logique'" (ref. 2), 300. Panteki also discusses Woodhouse's work on the three-body problem.
73. *Cf*. Becher, "William Whewell and Cambridge Mathematics" (ref. 51), 10.
74. Woodhouse, *Physical astronomy* (ref. 23), p. lviii. Analysis additionally provided the assurance that the system was stable, with overtones of desirable political and social stability; see Smith and Wise, *Energy and empire* (ref. 27), 153.
75. Woodhouse, *Elementary astronomy*, 2nd edn (ref. 66), p. xxii.
76. R. Woodhouse, "Some account of the transit instrument made by Mr. Dolland, and lately put up at the Cambridge Observatory", *Philosophical transactions of the Royal Society of London*, cxv (1825), 418–28; *idem*, "On the transit instrument of the Cambridge Observatory; being a supplement to a former paper", *Philosophical transactions of the Royal Society of London*, cxvi (1826), 75–76; and *idem*, "On the derangements of certain transit instruments by the effects of temperature", *Philosophical transactions of the Royal Society of London*, cxvii (1827), 144–58.
77. R. Woodhouse, "Review of Wood's Optics and Vince's Astronomy", *Monthly review*, xxxiv (1801), 239–45, p. 244, and *idem*, "Review of Wood's Mechanics and Vince's Hydrostatics", *Monthly review*, xxviii (1799), 313–23, p. 323.
78. Anonymous, "Notices", *London times*, 28 February 1823, 3G. Despite being the Plumian Professor, Woodhouse probably gained prestige through his marriage into the family of architect William Wilkens. Whilst his wife's death was noted in the *London Times*, the same was not true of Woodhouse's; see Anonymous, "Notices", *London Times*, 7 April 1826, 4B.
79. Enros, "The Analytical Society" (ref. 2), 244.

80. B. Powell, "Review of Woodhouse's Elementary Treatise on Astronomy", *British critic*, xx (1823), 143–56, pp. 145–56. See also P. Corsi, *Science and religion: Baden Powell and the Anglican debate, 1800–1860* (Cambridge, 1987), 37ff.

81. De Morgan, "Robert Woodhouse" (ref. 3), 527. The archival evidence unfortunately does not indicate where or how Woodhouse learned to be an "expert practical astronomer" before 1812, although he certainly had the resources to undertake such a task.

82. Anonymous, "Review of Woodhouse's Physical Astronomy" (ref. 54), 377.

83. O.15.47/381 in Whewell Papers, Wren Library, Trinity College.

84. On 'progressive' *v*. 'permanent', see R. Yeo, *Defining science: William Whewell, natural knowledge, and public debate in early Victorian Britain* (Cambridge, 1993), 209–30.

85. See Panteki, "French 'logique'" (ref. 2), 313–17, and Becher, "William Whewell and Cambridge mathematics" (ref. 51), 10–19.

86. Airy's copies still remain in the Wren Library.

87. Airy, *Autobiography* (ref. 42), 77–78.

88. Letter 47, 11 February 1828, Airy Papers, Wren Library.

89. Letter 46, 27 January 1828, Airy Papers, Wren Library.

90. Letter 48, 19 February 1828, Airy Papers, Wren Library.

91. G. Airy, *Mathematical tracts on physical astronomy, the figure of the Earth, precession and nutation, and the calculus of variations* (Cambridge, 1826), p. iv. See Panteki, "Boole's Mathematical Analysis of Logic" (ref. 2), 169–73, and *idem*, "Relationships between algebra, differential equations and logic in England, 1800–1860", Ph.D., Council for National Academic Awards, 1991, §1.3 for more on Airy's use of the Earth-figure equation, and *idem*, "French 'logique'" (ref. 2), 301 for Airy's movement toward Whewell.

92. G. Airy, *Mathematical tracts on physical astronomy, the figure of the Earth, precession and nutation, and the calculus of variations*, 2nd edn (Cambridge, 1831), p. iv. Woodhouse's work was reduced to two brief citations in this edition.

93. Panteki, "French 'logique'" (ref. 2), 316.

94. Airy, *Autobiography* (ref. 42), 29–30. Airy's autobiographical notes were never published during his lifetime.

95. G. Airy, "Report on the progress of astronomy during the present century", *First report of the British Association for the Advancement of Science* (1833), 125–89, pp. 185–6.

96. Airy, *Autobiography* (ref. 42), 37–38.

97. Schaffer, "Paper and brass" (ref. 2), 246–76. See also Schaffer, "Astronomers mark time: Discipline and the personal equation", *Science in context*, ii (1988), 115–45, and A. Chapman, "George Biddell Airy (1801–1892): A centenary commemoration", *Notes and records of the Royal Society*, xlvi (1992), 103–10, pp. 107–8.

98. Woodhouse's early articles could provide a fruitful link, for instance, between the narratives of I. Grattan-Guinness, "French calcul and English fluxions around 1800: Some comparisons and contrasts", in *Science and imagination in XVIIIth century British culture*, ed. by S. Rossi (Milan, 1987), 215–30; *idem*, *Convolutions in French mathematics, 1800–1840* (Boston, 1990); and Guicciardini, *Newtonian calculus* (ref. 1).

99. In explaining the lack of extant images of Woodhouse, a note in the picture album of Lucasian Professors in the Wren Library suggests that Woodhouse was unwilling to have any likenesses of him produced, apparently because of a pock-marked face.

100. Guicciardini, *Newtonian calculus* (ref. 1), 136.

101. Schaffer, "Paper and brass" (ref. 2), 255.