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MATHEMATICAL ANALYSIS AND PHYSICAL ASTRONOMY IN GREAT BRITAIN AND IRELAND, 1790-1831: SOME NEW LIGHT ON THE FRENCH CONNECTION

Alex D.D. Craik

Abstract. — The reception by British and Irish mathematicians of late-eighteenth-century French mathematical analysis, and its applications to astronomy, is here re-examined. The main early British participants were John Robison, John Playfair, Robert Woodhouse, John Toplis, John Brinkley, John West, William Spence, John Herapath, James Ivory, William Wallace, and Mary Somerville. Their activities and publications, and those of some others, are outlined. The reviews of John Playfair and Robert Woodhouse, many little-known, are highlighted. Finally, we discuss why, despite the work of these individuals, reform of British mathematics was at first so slow; and why, in contrast, the eventual modernisation of the Cambridge Mathematical Tripos examinations, following the efforts of Charles Babbage, John Herschel, George Peacock and others, led to rapid improvement.

Résumé (Analyse mathématique et astronomie physique en Grande-Bretagne et en Irlande (1790–1831) : quelques nouveaux éclairages sur les liens français)

On examine ici la réception à la fin du dix-huitième siècle, parmi des mathématiciens de Grande-Bretagne et d'Irlande, de l'analyse mathématique française et de ses applications à astronomie. Les premières contributions britanniques furent celles de John Robison, John Playfair, Robert Woodhouse, John Toplis, John Brinkley, John West, William Spence, John Herapath, James Ivory, William Wallace, et Mary Somerville. Cet article présente leurs activités et leurs publications, ainsi que quelques autres. Les comptes rendus de John Playfair et

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Robert Woodhouse sont étudiés de près. On analyse enfin les raisons pour lesquelles, en dépit des travaux de ces individus, la réforme des mathématiques en Grande-Bretagne a d'abord été si lente, et pourquoi la réforme du Cambridge *Mathematical Tripos*, elle, a finalement débouché sur une amélioration rapide.

1. INTRODUCTION

The several writers who deplored the decline of British mathematics during the latter half of the eighteenth century perhaps overstated the case. Certainly, there was no-one of the calibre of Newton. But, in the first half of the century, there were talented mathematicians, such as Taylor, De Moivre, Cotes, Colson, MacLaurin, Stirling, Landen, Waring, and Thomas Simpson who all espoused analysis, as well as the leading geometers Robert Simson and Matthew Stewart who influenced John Playfair. But mathematicians of other nations, particularly Euler, d'Alembert, Lagrange and Laplace, now led the way; and between 1750 and 1790 few British mathematicians followed their innovations. Importantly, there were no British institutions such as the nationally-sponsored Academies in Paris, Berlin and St. Petersburg to encourage, coordinate and support mathematical and astronomical research.

The Royal Society in London included many wealthy dilettanti among its fellowship; and, under the long presidency of the botanist and naturalist Sir Joseph Banks during 1778-1820, a marked antipathy had developed towards mathematics. Moreover, unlike in the European Academies, fellowship of the Society brought no financial rewards. Only near the end of our chosen period did effective scientific institutions begin to emerge; and only after the peace of 1815 did renewed scientific contacts between Britain and France begin to bear fruit. The Astronomical Society of London was founded in 1820 by several disenchanted fellows of the Royal Society, among them Charles Babbage and John Herschel (but not James Ivory); it became the Royal Astronomical Society in 1831. Also, after Banks' demise, some changes were made in the running of the Royal Society that improved the standing of mathematical subjects. The benevolent Society for the Diffusion of Useful Knowledge was founded in 1826, mainly by the politician and amateur mathematician and physicist, Henry, Lord Brougham. Then, in 1831, the British Association for the Advancement of Science was founded on the initiative of Brewster, Herschel, Babbage and others. This last year is chosen as the end-date of our study, for it marks the beginnings of a nation-wide scientific forum. It also happens to be the year of publication of Mary Somerville's influential *Mechanism of the Heavens* [Somerville 1831].

In mathematics, for too long there had been a reluctance to replace Newton's method of fluents and fluxions by the superior Leibnizian notation of the calculus and its subsequent improvements. But the first introduction of this "continental analysis" to Great Britain was not due to the Cambridge Analytical Society led by Charles Babbage, John Herschel and George Peacock, as was long claimed. Certainly, their 1816 English translation of Lacroix's *Traité élémentaire de calcul…* [Lacroix 1802], [1816], and Peacock's book of *Examples* [Peacock 1820] were used by students in Cambridge and beyond, and so contributed to the modernisation of British mathematics. But they were neither first nor alone: the matter is well put in Niccolò Guicciardini's *The Development of Newtonian Calculus in Britain 1700-1800* [Guicciardini 1989, 136]:

> The struggle for the reform of mathematical education at Cambridge has been mistakenly viewed as a process in which British mathematics was successfully reformed. Historians largely based this view on recollections of former members of the Analytical Society who liked to describe themselves as the originators of interest in continental mathematics and the revival of research in the first half of the nineteenth century. This is clearly false. They were anticipated by Woodhouse at Cambridge, and as we have seen there were several other centres of reform as equally important as Cambridge…

In fact, before 1816, numerous British and Irish mathematicians had read, reviewed, summarised and translated French analytical works, and some made original advances. Their achievements are the focus of the present paper. Much has already been described by [Guicciardini 1989], [2004], [Panteki 1987]; [1991], [Crosland & Smith 1978], [Grattan-Guinness 1985]; [1986], the present writer and others; but the extent of this awareness of French mathematical science has widely been underestimated. Here, the matter is examined afresh and some overlooked material is described. It is worth emphasising that the main focus of this paper is the reception of French analysis and its applications to astronomy: a more general account of British and Irish mathematics and its applications during the Hanoverian period is beyond its scope.

The general context is described in Section 2. Then Section 3 describes the necessary "prelude to change," in which some transitional figures interact with the works of French savants. Section 4 is devoted to the remarkable influence of Laplace's *Mécanique céleste* [Laplace 1799–1827], the achievements of some leading British analysts and astronomers, and further British-French interactions. Sections 5 and 6 summarise the influential and penetrating reviews of French, and some British, work by John Playfair and Robert Woodhouse respectively, many of which are little known to historians. Some concluding remarks are in Section 7. But, first, the intellectual, social and educational state of Britain and Ireland, and relations with France, are reviewed.

2. THE SOCIAL, EDUCATIONAL AND SCIENTIFIC SCENE

(a) *Education*

During 1790-1815, the British ruling classes feared that the French Revolution might spread to Britain, and the Napoleonic wars engendered hostility and erected a barrier both to trade (including that in books) and to visits between British and French scholars. In education, the radical structural changes that occurred in France had no counterpart in Britain. Conservative Cambridge primarily remained a training ground for a career in the Church of England, law, or education. It was also the fashionable place of study, or recreation, for sons of the nobility and landed gentry who sought no profession. However, the wealthy colleges supported many fellows, chosen from among their ablest graduates; and a few of these became tutors and professors. The highly competitive "Mathematical Tripos" examinations were the main focus of aspiration for able students, for a good place in the list of "wranglers" was almost certain to secure a college fellowship. For the honours B.A. degree, far less attention was paid to Latin, Greek and theology. Oxford, the other English university, was just as conservative, and did not favour mathematics to the same extent.

In the Scottish universities of St Andrews, Glasgow, Aberdeen and Edinburgh, the situation was very different. The Scottish tradition was more socially inclusive, and the Master of Arts degree was far less specialised, with compulsory classes in Latin, Greek, Moral Philosophy, Logic and Metaphysics, Mathematics and Natural Philosophy (physics). (Theology was also studied, but as a postgraduate degree, to train ministers for the presbyterian Church of Scotland.) Entrant students were usually younger than at Cambridge, and many were poorly prepared, so that much of the teaching was rather elementary though wide-ranging: see e.g. [Davie 1961]. Also, the Scottish universities had inadequate financial support and could not offer opportunities to their best graduates, such as the college fellowships at richly-endowed Cambridge and Oxford. Though few

Cambridge dons and students were motivated or inspired by the industrial revolution then underway, many Scots became involved in it.

Intellectual life in Scotland, and particularly in Edinburgh and Glasgow, was still conditioned by the Scottish Enlightenment that flowered from the mid-eighteenth to the early-nineteenth century. There had been influential treatises by Adam Smith, David Hume, Adam Ferguson and Thomas Reid. There were also strong traditions in mathematics and in natural philosophy: Matthew Stewart and Robert Simson emphasised geometry, but Colin MacLaurin and James Stirling also embraced more modern analytical methods. Major publishing ventures were undertaken, such as the *Encyclopaedia Britannica*, first issued in 1768 in three large volumes and later much expanded. This and later rival British encyclopaedias, especially the *Edinburgh Encyclopaedia* and the London-based *Encyclopaedia Metropolitana* and Abraham Rees's *Cyclopaedia*, did much to educate a general population that, in Scotland though not throughout England, already benefited from a widespread system of elementary parochial schools.

A notable characteristic of aspiring academics and intellectuals in Scotland, much less evident in England, was that most were wide-ranging generalists, rather than specialists in a single discipline. In part, this reflected Enlightenment ideals and the inclusive nature of the Scottish Master of Arts degree: this produced graduates proficient in classical languages and moral philosophy as well as in mathematics and natural philosophy (and many who went on to study theology and divinity). Such versatility was necessary for those hoping to secure a university post, then few in number: applicants had to maximise their chances of success by professing a range of disciplines [Craik & Mann 2011]. Scottish professors, unlike their counterparts in Oxford and Cambridge, were keen to write for encyclopaedias: such ventures were in tune with their generalist outlook, provided good remuneration to enhance their usually low salaries, and were less risky than writing advanced treatises for a small readership. [1]

In the early nineteenth century, and despite chronic under-funding, Edinburgh University was the premier British university if measured by the prestige of its professors: it had a high reputation in medicine, science and

1 Scottish professors received a low salary that was augmented by class fees paid by the students who attended. In Cambridge and Oxford, the remuneration of professors and fellows varied, depending on the size of the endowments and on college income from property rents. Some, such as the Lucasian chair of mathematics, were poorly paid; but all fellows benefited from subsidised college meals and accommodation, as many still do today.

the humanities, and it attracted students from afar [Grant 1884]. In contrast, the main attractions of Oxford and Cambridge were the social and occupational advantages that the richer colleges were able to impart to their graduates. As well as college fellowships, many "livings" of the Church of England were in their gift, and they had close links with the London Inns of Court that dominated legal training and practice in England [Winstanley 1940], [Craik 2007].

Ireland was for long ruled as a British colony, with a large disadvantaged Catholic majority and a relatively well-to-do Protestant minority that owned most of the land and wielded political power. In an attempt to regularise the situation, in 1801 Ireland became part of the United Kingdom of Great Britain and Ireland, with representation in London's Westminster parliament. There was then just one university, the University of Dublin, with Trinity College as its sole college founded in 1592 with strong links to Cambridge. Until 1873, it was the university of the Protestant ascendancy, in which all professors and fellows were Protestants and usually Episcopalians. Although Catholic students were permitted to enter from 1793 onwards, they were discouraged from attending by the Catholic Church itself. Given its strong Episcopalian connections, it is unsurprising that several Cambridge graduates became professors there. But standards in mathematics were low. For long, not even Newton's theory of fluxions was taught; then, around 1812, Irish mathematics went straight from no calculus at all to the "continental" differential and integral calculus [McConnell 1944].

Also, it should not be forgotten that gifted amateurs, some with little or no university education, made original contributions to mathematics and natural philosophy. In particular, throughout our period, much of British and Irish observational astronomy was conducted by enthusiastic gentlemen amateurs, rich enough to build and operate their own observatories. Some of these, rightly dubbed "Grand Amateurs" by [Chapman 2011], made observations of ground-breaking importance.

If there were some tensions between Scotland and England, so much greater were those between Britain and France. Politically, militarily, religiously and philosophically, relations between the two countries were at a low ebb between 1780 and 1815. British government policies were repressive for fear of political contagion; and the established churches, Episcopal and Presbyterian, wielded much political power. As a result, academics throughout Britain and Ireland had to play safe if they were to avoid charges of suspected Jacobinism or atheism, and Roman Catholics were expressly excluded from university posts. Such issues arose in more than one university appointment, such as John Leslie's in Edinburgh [Morrell 1975]. With emphasis on Edinburgh, the "Theophobia Gallica" is comprehensively explored by [Morrell 1971], who also exposes the oppressive mix of political and religious intolerance then rife in Scotland. Yet, despite anti-French hostility and marked differences of outlook, some British scholars recognised the important advances taking place in French mathematical science; and further improvements followed the end of war in 1815. The scholars of this time played a crucial role in preparing the way for the British scientific revival of the mid-nineteenth century.

(b) *Astronomy*

The main national facility was the Government-funded Royal Observatory at Greenwich, founded in 1676 and overseen by the Astronomer Royal. The most important private observatories during our period were William Herschel's, which operated in Slough from 1774, and James South's at Kensington, London, built around 1826.

British advances in observational astronomy were impressive. The German-born William Herschel (1738-1822), aided by his sister Caroline Herschel (1750-1848), not only created the most comprehensive map of the stars of the northern hemisphere, but also discovered a new planet, now named Uranus but then known as the "Georgian Planet". They also studied double stars, aided by James South, and recorded a huge number of new nebulae (or galaxies). Also, the accurate observations of successive Astronomers Royal, James Bradley (1693-1762) and Nevil Maskelyne (1732-1811), were later allied with Laplace's new theory, by both Bürg in Vienna and Delambre in Paris, to prepare up-to-date solar, lunar and planetary tables.

Among French works on astronomy, Joseph-Jérome Lalande's *Traité d'astronomie* (1764 and later editions) was deservedly well known in Britain. The third edition [Lalande et al. 1792] had Jean-Baptiste-Joseph Delambre and Charles Mason (1728-1786) as co-authors: an early instance of Franco-British cooperation.[2] Mason was assistant astronomer at the Greenwich Observatory, and surveyed the Mason-Dixon line in the U.S.A. Lalande also edited the astronomical *Connaissance des temps,* the French equivalent of the British *Nautical Almanac,* and in 1802 he completed the

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2 During the 1780s, the Paris Observatoire collaborated with the Royal Society of London on new observations to establish the difference in longitude between the Paris and Greenwich meridians [Martin & McConnell 2008]. Some cooperation between observers continued even during wartime.

final two volumes of Montucla's *Histoire des mathématiques* [Montucla & Lalande 1799–1802]. These and the *Tables Astronomiques* of Delambre and Bürg [Delambre & Bürg 1806], to be discussed below, were also known to British astronomers, as was Delambre's lengthy *Rapport historique sur les progrès des sciences mathématiques* [Delambre 1810] that was reviewed by Playfair.

Soon after leaving Cambridge around 1816, William Herschel's son John gave up his pure mathematical researches to follow in his father's footsteps as a practising astronomer. He continued his father's and aunt's work in mapping the "fixed" stars of both the northern and southern hemispheres [Warner 1994]. The mapping of stars was a task that required considerable, but by then routine, mathematical calculations to determine the exact position of each star from that observed: it was necessary to take into account the Earth's rotation, its orbit round the Sun, its "wobbling" precession and nutation about the mean axis of rotation, and atmospheric refraction and aberration of the light rays entering the telescope.

More taxing mathematically was prediction of the orbits of planets and comets, and of the moon and other planetary satellites. This was then called "physical astronomy" as it ultimately relied on Newton's law of gravitation. As a first approximation, orbits were conic sections; but there were well-known, if small, deviations from these. To account for them, the perturbation theories of Laplace for deriving approximate solutions to the famously difficult "three body problem" were fundamental. His analytical methods, allied with observations to determine several unknown constants that arose in the theory, underlay the improved tables that described the perturbations of lunar and planetary orbits, and of the moons of Jupiter. The theory of probability, as extended by Laplace, was also employed to deduce the most likely orbit of a celestial body from a number of observations that inevitably contained small inaccuracies. It is undoubtedly true that, at this time, it was physical astronomy that provided the main spur for advances in mathematics, with Laplace and his followers leading the way.

The frequent eclipses of the moons of Jupiter had been used since the time of Galileo to determine longitude, for they provided a "heavenly clock," more accurate than any mechanical one. But, though the method worked well on land, it was impractical at sea, as satisfactory telescope observations could not be made from a pitching and rolling vessel. The national observatories in Greenwich and in Paris were set up specifically to provide a means of improving navigation at sea; and the preferred method was the construction of "lunar distance tables," that would show the angular distance of the Moon from the Sun and from other fixed stars at noon in Paris or Greenwich on any given day. But, though the Moon was easier to observe than the distant moons of Jupiter, the matter was complicated by the apparently erratic perturbations of its orbit. Here, Laplace's theory, allied to observations, was indispensable. But, given accurate lunar tables and good sextant observations from on ship, the navigator still had to carry out lengthy calculations in order to determine his longitude. [3]

The greatest triumph of Laplacian astronomical theory occurred later, when the planet Neptune was discovered. Observed perturbations of Uranus could not entirely be accounted for by the influence of Saturn and Jupiter, and the existence of a further unknown planet was suspected. Analyses performed independently by Urbain Le Verrier in Paris and John Couch Adams in Cambridge predicted its location in 1845; and observational confirmation, based on Le Verrier's work, was soon accomplished by Johann Galle at the Berlin Observatory. Unfortunately, a bitter priority dispute was whipped up between British supporters of Adams and French supporters of Le Verrier. Subsequent enquiries showed that both Cambridge's James Challis and the Astronomer Royal, George Airy, could have made the first confirmation, based on Adams' calculations, but failed to do so [Standage 2000], [Kollerstrom 2006].

(c) *Mathematics*

For long, Euclidean geometry held pride of place in the British and Irish universities as the one truly rigorous branch of knowledge. Though the power of algebra and analysis was recognised, their foundations were still considered insecure, unless supported by geometrical reasoning. Before about 1825, the unwritten Cambridge syllabus in mathematics was characterised by adherence to Euclidean geometry and to Newton's *Principia* and his theories of fluxions and infinite series. Even later, when reform was in the air, a distinction was made between "permanent studies" (Euclidean geometry, some algebra, and Newton's geometrical applications to astronomy in his *Principia*), and "progressive studies" (such as calculus and analysis, electricity and magnetism) that were areas of current advances, but the foundations of which were still thought doubtful. This

[3] Only with the development of accurate and *inexpensive* ships' chronometers by John Arnold and Thomas Earnshaw, following the pioneering inventions of John Harrison during 1730-70, were the lunar tables eventually superseded [Sobel 1996]. According to Sobel, around five thousand marine timekeepers were in use worldwide by 1815.

distinction was most clearly propounded by William Whewell [Whewell 1836], [1845]: see e.g. [Smith & Stray 2001]. However, as cogently argued by [Guicciardini 2004], the achievements of eighteenth-century British mathematicians in following and modifying Newton's ideas must not be underestimated: some fundamental advances in geometry were achieved, most notably by Roger Cotes, Robert Simson, Matthew Stewart and James Glenie—see [Guicciardini 2004], [Tweddle 2000], [Craik 2009]. An authoritative recent survey of British geometry research, textbooks and teachers during 1750-1830 is [Bruneau 2015].

Newton's theory of fluxions and fluents was based on his notion of "prime and ultimate ratios": a limiting process involving motion. Despite its undoubted success, debate had long raged over its validity, as many rejected the idea of ratios of vanishingly-small quantities; and Leibniz's differentials were considered equally unsatisfactory. Notably, Colin MacLaurin's two-volume *Treatise of Fluxions* [MacLaurin 1742] supplied a rigorous geometrical foundation for Newton's theory, employing the Archimedean "method of exhaustion"; and, in the second volume, presented a comprehensive account in Newtonian "dot" notation that incorporated new physical applications. MacLaurin's treatise became well known to French mathematicians [Grabiner 1997], [2002], [Guicciardini 2004], [Bruneau 2011]. But others considered Newton's and MacLaurin's introduction of motion as both unnecessary and undesirable. Alternative formulations were sought by, among others, John Landen in his "Residual Analysis" [Landen 1758] and James Glenie in his "Antecedental Calculus" [Glenie 1793]; [1798], but neither of these found favour. In France, an attractive alternative was proposed by Lagrange and Laplace, in which it appeared that only finite quantities were required. All that was necessary was that a mathematical function, say $f(x)$, had a convergent Taylor-series expansion about any chosen point $x = a$, as

$$f(a+y) = f(a) + Ay + \frac{B}{2!}y^2 + \frac{C}{3!}y^3 + \cdots ,$$

where y is any suitably-small but *finite* quantity. In this case, A, B, C etc. are *defined* to be the successive derivatives of $f(x)$ at $x = a$. This approach was espoused, with some *caveats*, by Cambridge's Robert Woodhouse. His former students Babbage and Herschel concurred, and strongly promoted this view in both the Analytical Society *Memoirs* [Analytical Society 1813], and in their translation, with additional notes, [Lacroix 1816]. But it was later recognised as defective, both because it is restricted to those functions that have Taylor-series expansions, and because it is often unclear how this expansion can be derived without calculus. [4]

In contrast, others sought to establish the calculus by a more rigorous limit process, that of MacLaurin being rightly considered unwieldy and elaborate. A worthy attempt was made by William Wallace in [Wallace 1815]; and the matter was finally resolved in favour of a limit-based formulation by Cauchy and Bolzano in the 1820s. This issue has been much studied by historians: see, for example, [Grattan-Guinness 1970], [Grabiner 1978], [Bottazzini 1986], [Fraser 1987], [1989] and, from an English standpoint, [Richards 1991].

Another debate, then still current, was the status of imaginary and complex numbers, that had no foundation in geometry, but which were known to yield correct results in algebra (for example, the roots of cubic equations). John Playfair consistently maintained that they merely suggested analogies between properties of circles and hyperbolae, which then required proofs by geometrical means; but the younger Robert Woodhouse was more hopeful that they formed the basis for truly logical proofs. The work of then little-known mathematicians Wessel, Argand and Buëe was soon to clarify the situation. [5]

The most successful applications of mathematics were to astronomy and mechanics, where the governing equations were supplied by Newton's laws, and where Laplace's analytical methods had made astonishing progress. But, before then, geometrical methods were still preferred, most notably by Edinburgh's Matthew Stewart [Stewart 1746], [1761], [1763], who treated astronomical problems as well as pure geometry. The novelty of Stewart's theorems, now easily overlooked, is that they extend the scope of Euclidean geometry to encompass lines defined algebraically by powers of quantities greater than three. [6]

Before 1815, summaries, translations and extracts of many French works on physics—especially heat, light and electricity—were printed in several British journals, most notably Thomas Thomson's *Annals of Philosophy*, Brewster and Jameson's *The Edinburgh Philosophical Journal*, William Nicholson's *Journal of Natural Philosophy, Chemistry and the Arts*, and *The*

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4 The theory of finite differences had been developed in Britain by Brook Taylor, James Stirling and William Emerson before being taken up in France by Lagrange, Laplace and Lacroix.

5 See also Section 7 below.

6 After his death, others published geometrical demonstrations of the many propositions that he had stated without proof: the most successful was James Glenie [Glenie 1812]. See [Craik 2009].

Philosophical Magazine. In particular, a translated review by J.-B. Biot of the first three books of Laplace's *Mécanique céleste* was published in parts in the *Philosophical Magazine* [Biot 1809]. Such connections between France and Britain in physics are more fully reviewed by [Crosland & Smith 1978] and [Miller 1986]. Siméon Denis Poisson's *Traité de mécanique* [Poisson 1811] was particularly well known and was eventually translated into English by Henry Harte in 1842; and the works of Ampère, Fresnel, Arago and Fourier on optics, heat, electricity and magnetism were of great significance. When, in 1828, George Green published his important, but long neglected, *An Essay on the Application of Mathematical Analysis to the Theories of Electricity and Magnetism* [Green 1828], he regretted that he had access only to limited sources of information, but mentioned that he had read works by Poisson, Arago, Laplace, Fourier and Cauchy.

Mathematical translations and summaries appeared in the *Mathematical Repository,* prepared by William Wallace and James Ivory, in what Wallace later described as "a revolutionary spirit" to promote continental analysis. Influential encyclopaedia articles were published in the *Encyclopedia Britannica* and its *Supplement,* in the *Edinburgh Encyclopaedia,* in Rees' *Cyclopaedia* and in the *Encyclopaedia Metropolitana,* that sometimes drew on French sources.

British adoption of "continental analysis" and, with it, the gradual reduction of emphasis on geometry, was encouraged by the reviews and articles of Toplis, Playfair and Woodhouse in the early years of the nineteenth century, and then by the expository works of Woodhouse, Wallace, Ivory, Brinkley, Babbage and Herschel. Their reworkings contained interpretations and demonstrations of some originality, as also did the tardily-published treatises of John West. Genuine advances were made in researches by Spence, Ivory, and later Herschel and Babbage. At the end of our chosen period, Somerville's masterly exposition of Laplacian astronomy was an appropriate culmination. This slow change in intellectual climate was brought about by these and other scattered individuals, many with no paid *mathematical* employment. Their advances were a necessary precursor of the later surge, originating in Cambridge around 1830, that established a dominant research presence in physical applied mathematics and a distinctive school of algebra, achieved by a growing class of professional mathematicians.

3. PRELUDE TO CHANGE

To illustrate the changes that needed to occur, we briefly mention some unreformed and transitional British mathematicians.

Nicolas Vilant (1737-1807), professor of Mathematics at St Andrews, was a long-term invalid who employed a series of assistants to teach in his stead. He published just one work: *The Elements of Mathematical Analysis, abridged for the use of students* [Vilant 1783/1798], and he left many manuscripts that are drafts for a more comprehensive treatise. Though his is probably the first book in English to use the phrase "mathematical analysis" in its title, it owes nothing to the analysts of France, or indeed to Euler. Rather, its account of algebra and infinite series is in the style of MacLaurin and Newton. Yet, several of Vilant's students went on to pursue original mathematics, the most notable being James Glenie, John West, James Ivory and John Leslie [Craik 2009], [2012].

At Cambridge, Isaac Milner (1750-1820) was Jacksonian Professor of Natural Philosophy, 1783-92, Lucasian Professor of Mathematics, 1798-1820, (Anglican) Dean of Carlisle Cathedral, 1791-1820, and a despotic President of Queens' College. According to the Cambridge historian Gunning, "the University perhaps never produced a man of more eminent abilities" [Gunning 1854]; but he gave no lectures as Lucasian professor of mathematics [Knox 2004]. Yet he was probably abreast of advances being made in France. For, on his death, he bequeathed many books to his college, including works by Laplace, Lacroix, Legendre, Poisson and Biot [Cannell 2001, 26]. He must have influenced John Toplis, who was a student and later a fellow and Dean of the college.

In September 1804, John Playfair (1748-1819), then joint Professor of Mathematics at Edinburgh but soon to transfer to the chair of Natural Philosophy, paid a visit to Cambridge. His veneration of Cambridge's illustrious past contrasts with his criticism of its present state: "One must however regret that the institutions which have answered so noble a purpose have not kept pace with the improvements of knowledge, and do now not infrequently retard the Growth of Sciences which in their infancy they served so happily to nurse..." [Playfair 1804]. [7]

Playfair's lack of fondness for the English universities no doubt also stemmed from his political views: he was a staunch Whig, whereas Oxford and Cambridge were then dominantly Tory. In addition to a well-known

7 This quotation, from a letter to Miss Berry of Shrewsbury Hall, Twickenham, is addressed to just one of Playfair's many female correspondents: himself unmarried, he enjoyed the company of many "society ladies".

work on geometry [Playfair 1795], his geological *Illustrations of the Huttonian Theory of the Earth* [Playfair 1802], and a two-volume *Outlines of Natural Philosophy* [[Playfair] 1812], [1814a], Playfair published lengthy and authoritative essays in the *Edinburgh Review*, some of which are mentioned below. The *Edinburgh Review* was politically important, showcasing Whig opinions that accorded with Playfair's own; and he gladly received handsome fees from its publisher, Archibald Constable. Late in life, Playfair also wrote an impressive "Dissertation exhibiting a General View of the Progress of Mathematical and Physical Science since the Revival of Letters in Europe" for the second and fourth volumes of the Supplement to the 4th edition of the *Encyclopaedia Britannica*. This is reprinted in [Playfair 1822, vol. 2].[8]

John Robison (1739-1805) was John Playfair's predecessor as professor of natural philosophy at Edinburgh, and the two colleagues were good friends with broadly similar political and scientific opinions.[9] A great admirer of Isaac Newton, Robison was also remarkably well read in the continental literature of the eighteenth century. His four-volume *A System of Mechanical Philosophy* [Robison 1822] compiled after his death by David Brewster, reprints several of his longer articles for the *Encyclopaedia Britannica* (3rd edn. 1793-1801) and also most of his *Elements of Natural Philosophy…* [Robison 1804].[10] This last, the only published volume of a projected larger work, is devoted to mechanics and physical astronomy. Playfair judged it "highly estimable, and… entitled to much more success in the world than it has actually had" [Playfair 1822, **4**, 174].

The *Elements* contain many references to continental literature, both historical ones to Leibniz, Johann Bernoulli, d'Alembert, Euler, Boscovitch and others, and also to more contemporary works by Lagrange, Laplace and other French writers. Though his own use of mathematics was sparing, and he preferred to use fluxions instead of the "continental" calculus, Robison was familiar with French work on mechanics, the resistance of bodies moving in fluids, and both observational and theoretical

8 Playfair died before he could finish his dissertation, which extends only to about 1700. Only the first section of its second part was published, on the period of Newton and Leibniz: he had planned further sections on Euler and d'Alembert and on Lagrange and Laplace. John Leslie completed the task just before his own death.

9 Following Robison's death, Playfair wrote an interesting account of Robison's unusually eventful life and career for *Trans. Roy. Soc. Edinburgh*, **7** (1815), reprinted in [Playfair 1822, **4**, 119-178]. Sympathetic but not uncritical, Playfair is dismissive of Robison's belief in a Europe-wide political and religious conspiracy, expounded in a then-popular book [Robison 1798].

10 For convenience, specific page references are given below only to the *System*.

"physical" astronomy. The following quotations illustrate his reading and opinions.

Lagrange's *Mécanique analytique* is described as [Robison 1822, **1**, 157-158]:

> ... full of the most ingenious and elegant solutions of very interesting and difficult problems; and all this without drawing a line or figure, but accomplishing the whole by algebraic operations.
>
> But this is not teaching mechanical philosophy; it is merely employing the reader in algebraic operations,... without any notions, distinct or indistinct, of the things, or the processes of reasoning that are represented by the symbols made use of.

On one aspect of the three-body problem of astronomy, the perturbation of the Earth's orbit due to Jupiter, Robison wrote [Robison 1822, **3**, 165]:

> Euler, D'Alembert, De la Grange, Simpson, and other illustrious cultivators of this philosophy, have immensely improved the methods pointed out and exemplified by Newton, and, by more convenient representations of the forces..., have at last made the whole process tolerably easy and plain. But it is still only fit for adepts in the art of symbolic analysis. Their processes are in general so recondite and abstruse, that the analyst loses all conception, either of motions or of forces, and his mind is altogether occupied with the symbols of mathematical reasoning. [11]

The clash of Robison's religious and philosophical views with Laplace's apparent atheism is expounded in the concluding section of his "Physical Astronomy" [Robison 1822, **3**, 392-402] reprinted from his *Elements.* There, he takes issue with "a passage in M. de la Place's beautiful Synopsis of the Newtonian Philosophy, published by him in 1796, under the title of *Systeme du Monde*". His objection centres on Laplace's omitting any mention of a divine Creator: this is the "Theophobia Gallica" that was anathema to both Robison and the former Church of Scotland minister John Playfair [Morrell 1971]. Robison felt obliged to counter it: "Charged as I am with the instruction of youth—the future hopes of our country—it is my bounden duty to guard their minds from every thing that I think hazardous" [p. 399]. [12]

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11 Elsewhere, Robison discusses Laplace on the irregularities of Jupiter and Saturn [Robison 1822, 3, 169]; and objects to his treatment of Saturn's ring [Robison 1822, 3, 265-7], and of oceanic tides [Robison 1822, 3, 377].

12 The influence of Common Sense philosophy on the physical and mathematical attitudes of Robison, Playfair, Brougham and Leslie is examined by [Davie 1961] and [Olson 1975]; but Davie's views about the supposed Scottish preference for geometry over analysis are overstated.

Robison's interactions with French mathematical science, dating roughly from the period 1790-1805, are among the earliest in Britain. They show his appreciation of its achievements, along with sometimes-valid criticisms and his frustration with the intricacy of the analysis involved. But Robison's *Elements* seems to have had little influence, appearing just a year before his death; and his reprinted *System* was too long delayed to be useful.

Robison's colleague and successor, John Playfair, was also familiar with much continental scientific work. His essay reviews are mentioned below; and his later two-volume *Outlines of Natural Philosophy...* [[Playfair] 1812], [1814a] gives many references to Laplace, Legendre, Lagrange and earlier writers. But, though he taught some differential calculus when Professor of Mathematics, the mathematical content of his *Outlines* is slight. Nor did he employ differential calculus in any of his research papers. He and Robison are characteristic of most early British readers of French analysis—themselves unable to use it in original work, however much they appreciated its achievements.

Into this latter category also falls John Leslie [13], Playfair's successor as Professor both of Mathematics and then of Natural Philosophy in Edinburgh. According to an anonymous obituarist, "... with the higher departments of the new analysis he [Leslie] had a very slender acquaintance, and he was altogether unable to wield it successfully as an instrument of investigation" [Anon. 1835, 217]. Nevertheless, Leslie was willing to review advanced mathematics in his posthumously-published *Dissertation Fourth on the Progress of Mathematical and Physical Sciences chiefly during the Eighteenth Century* [Leslie 1842]. Though rightly criticised as "frequently sketchy and superficial" [Anon. 1835, 221], Leslie's survey is wide-ranging, and shows at least a general awareness of the methods of analysis, and an appreciation of its impressive achievements in the physical and astronomical sciences.

Another who deserves mention is the Edinburgh-educated Henry Brougham (later Lord Brougham), who maintained a keen interest in mathematics and physics while pursuing a high-flying legal and political career. There is a huge literature both by and about him, much of it political and legal, but some of it scientific and biographical: e.g. [Brougham & Vaux 1872–73]. As a co-founder of the *Edinburgh Review*, he wrote many of its early articles on a wealth of topics, including some on mathematics and physics [Schneider et al. 1945]. Though now remembered more as

13 Birth and death dates omitted in the text appear in Table 1 below.

a commentator than a practitioner of mathematics and physics, he published several papers, mainly on geometry; and late in life he collaborated with Cambridge's E.J. Routh to write an *Analytical View of Sir Isaac Newton's Principia* (1855). He had a wide scientific acquaintance and a strong desire to foster the study of science. He held high office in Parliament (for a time as Lord Chancellor), and was a main figure in the "Society for the Diffusion of Useful Knowledge" that published low-cost works on science and the arts, for which he wrote several tracts.

Published a little earlier than Robison's *Elements*, Charles Hutton's (1737-1823) two-volume *Mathematical and Philosophical Dictionary* [Hutton 1795–96] had a wider readership: it too cites numerous French publications, including recent works by Lagrange and Laplace, but gives few details.[14] Hutton was perhaps the best-known English mathematician of his day, and certainly the most prolific. Based at the Royal Military Academy at Woolwich, he and his colleagues and successors John Bonnycastle, Peter Barlow and Olinthus Gregory (1774-1841) wrote elementary textbooks, such as [Hutton 1798], and compiled mathematical tables. Hutton's collected *Mathematical Tracts* [Hutton 1812] describe important experiments on ballistics, geodetical work to determine the Earth's density, and some work on infinite series.[15] But the mathematics of Hutton and his colleagues, like Robison's, was firmly in the Newtonian tradition [Guicciardini 1989, 109-113]. Their French contacts were limited: Hutton translated Ozanam and Montucla's *Recreations in mathematics and natural philosophy* [Ozanam & Montucla 1803]; Bonnycastle translated Charles Bossut's *History of Mathematics* [Bossut 1803] and is the probable author of an article "Function" for Rees' *Cyclopaedia* that shows influence of Lagrange [Guicciardini 1989, 120]; Barlow did some work on electromagnetism that was influenced by Ampère's [Crosland & Smith 1978, 24-28], and his articles for the *Encyclopaedia Metropolitana* show awareness of continental work, despite using fluxional notation. He also published *A New Mathematical and Philosophical Dictionary…* [Barlow 1814], shorter and more compact than Hutton's. Gregory's textbooks, including one on astronomy [Gregory 1803], favoured geometrical over analytical exposition, arranged as propositions, corollaries and scholia: these now seem hopelessly outdated, but are a salutary reminder that such an approach still seemed sensible to some in the early nineteenth century. Gregory's only significant French interaction was with Jean-Baptiste Biot, whom

14 A review of this work by Robert Woodhouse is discussed in section 8 below.

15 Playfair's review of this is discussed in section 7 below.

he accompanied to the Shetland Islands in 1817 to make a survey and conduct pendulum studies to establish the figure of the Earth and the variation of its gravity with latitude: see [Playfair 1822, **4**, 531].[16]

At the Royal Military College at Marlow, later Sandhurst, the teaching was even more elementary under Isaac Dalby (1744-1824) [Guicciardini 1989, 114]. However, the appointments of William Wallace and James Ivory led to more ambitious projects, described below.[17]

Samuel Vince (1749-1821) was Cambridge's Plumian Professor of Astronomy during 1796-1821. His elementary astronomy works contain only a few passing references to Lagrange and Laplace, and give no indication of the major theoretical advances that they had made. But the third volume of his *A Complete System of Astronomy* [Vince 1797–1808], to be discussed below, was devoted entirely to solar, lunar, planetary and other tables based on Laplace's theory.

Vince's *The Principles of Fluxions*, written for students at the university, was first published in 1795. The final, fifth edition "corrected and enlarged throughout" was retitled *A Treatise of Fluxions* [Vince 1818]. Though this was published two years after the English translation of Lacroix's *Traité élémentaire* [Lacroix 1816], Vince dismisses the "continental" differential notation in a footnote (p. 2). Nevertheless, Vince's book contains a wealth of examples on differentiation, integration, maxima and minima and their applications: see also [Guicciardini 1989, 124-126]. A large part of Vince's work was appropriated by William Dealtry (1775-1847), whose *The Principles of Fluxions...* [Dealtry 1810] was the last textbook to be written on fluxions. His second edition of 1816 was savagely reviewed in the *Edinburgh Review* [[Playfair?] 1816] for its many defects: see also [Guicciardini 1989, 126]. Vince's *The Principles of Hydrostatics...* first published in 1796, reached a final, fifth edition in 1820 [Vince 1820]. Suffice to say that it might have been written at any time in the previous seventy years: practically the only continental references are to Galileo, Pascal, Daniel Bernoulli and d'Alembert, with no mention of Euler, Lagrange or Laplace.

Among the earliest to deplore the poor state of Britain's mathematics and the perils of publication was John Toplis. Toplis had studied at Queens' College, Cambridge, then became a school headmaster in Nottingham before obtaining a parish as an Anglican priest. When in Nottingham, Toplis is believed to have influenced the young George Green, though evidence

16 Their collaboration did not go well: see [Grattan-Guinness 1990, 187-188].

17 A study of mathematical education at the British military colleges is presently being undertaken by Olivier Bruneau.

is circumstantial [Cannell 2001]. In 1805, he published a long article in the *Philosophical Magazine,* entitled "On the Decline of Mathematical Studies, and the Sciences dependent upon them" [Toplis 1805]. Toplis complained that:

> It is a subject of wonder and regret to many, that this island, after having astonished Europe by the most glorious display of talents in mathematics and the sciences dependent upon them, should suddenly suffer its ardour to cool, and almost entirely to neglect those studies in which it infinitely excelled all other nations...
>
> Perhaps one reason to be assigned for the deficiency of mathematicians and natural philosophers is the want of patronage. These sciences are so abstruse, that, to excel in them, a student must give up his whole time, and that without prospect of recompense; and should his talents and application enable him to compose a work of the highest merit, he must never expect, by publishing it, to clear one-half of the expense of printing. All those men, therefore, who have not fortune sufficient to enable them to give up their time in the study, and part of their property to the publication, of works in these sciences, are in a manner excluded from advancing them. In France and most other nations of Europe it is different: in them the student may look forward to a place in the National Institute or Academy of Sciences, where he will have an allowance sufficient to enable him to comfortably pursue his studies; and should he produce works worthy of publishing, they will be printed at the expense of the nation.
>
> It is remarkable, that amongst the very few men who still pursue mathematical studies in this country, a considerable part, instead of being dazzled and delighted by the wonderful and matchless powers of modern analysis, still obstinately attach themselves to geometry...

Such views were still being expressed much later. In 1830, Charles Babbage bemoaned the backward state of science in England in his polemical *Reflections on the decline of science in England and some of it causes* [Babbage 1830], in which he quotes similar sentiments of John Herschel; while David Brewster extended the criticisms to Scotland [[Brewster] 1830-31a], [1830–31b]. These authors certainly had political and personal agenda, but their opinions cannot be dismissed as mere polemic. Despite some genuine achievements, particularly in the first half of the eighteenth century, the accusation that British mathematics (at the research level) was in serious decline by 1800 is a valid one; and identification of the educational and institutional causes was well founded.

The coming changes are well exemplified by William Wallace, who, from humble origins, was encouraged by Robison and Playfair and went on to hold Edinburgh's chair of mathematics. As a young man in 1792, he possessed seventy-six mathematical books, mostly on geometry, conic sections, trigonometry, algebra, series and fluxions: of these, there were just two "continental" works, Jakob Bernoulli's *Ars conjectandi* and Jakob

Hermann's *Phoronomia* [Craik & O'Connor 2011]. Yet, some years later, Wallace had re-educated himself: in his *Edinburgh Encyclopaedia* article "Fluxions" [Wallace 1815], he lists as further reading many French works, including quite recent ones, by Lacroix, Lagrange, Bossut, Carnot, Ampère, Du Bourguet, Garnier and Legendre. Indeed, Wallace's long article was the first complete account in English of the differential and integral calculus in "continental" notation, published one year before the Analytical Society translation of Lacroix: [Panteki 1987], [Guicciardini 1989, 120], [Craik 1999].

4. BRITISH SCIENTISTS, THE *MÉCANIQUE CÉLESTE*, AND OTHER FRENCH WORKS

No work was more influential than Laplace's *Mécanique céleste* [Laplace 1799–1827] in bringing about the modernisation of British mathematics. This was largely because it considered matters that Newton had pioneered in his revered *Principia*; but it adopted an analytical rather than geometric approach, the success of which could no longer be ignored. First to translate a part of this work into English was the same John Toplis, who published *A Treatise upon Analytical Mechanics; being the first book of the Mecanique Celeste of M. le Comte Laplace,...* [Toplis 1814]. Though Toplis restricts himself to just the first, introductory book of the *Mécanique céleste* (which amounted to sixteen books comprising five volumes), he nevertheless found it necessary to add many long explanatory notes to make the work intelligible to British readers. One enormously long note is a translation of the entire second chapter of Lagrange's *Mécanique analytique* [Lagrange 1788]. His translation remains faithful to the original, but he supplies several diagrams so notably absent from Laplace's and Lagrange's works. This is in marked contrast with the later reworking by Thomas Young, who "flatters himself... that he has rendered it perfectly intelligible to any person, who is conversant with the English mathematicians of the old school only, and that his book will serve as a connecting link between the geometrical and algebraical modes of representation" [[Young] 1821]: see also [Craik 2010a], [Robinson 2006].

Laplace's non-mathematical *Exposition du système du monde* was translated into English by John Pond [Laplace 1809], who was Astronomer Royal at Greenwich during 1811-1835 [Murray 2004]. An accurate translation of the first two books of the *Mécanique céleste* was later given by Henry Harte of Dublin [Harte 1822, 1826]. Though Harte had hoped to translate and annotate the first ten books, the project was dropped, almost certainly because of poor sales and high costs: indeed, few copies of the two published volumes have survived [Grattan-Guinness 1987]. One may question the need for translations into English, as most British and Irish scholars of that time knew sufficient French for reading, if not for conversation; but the copious explanatory notes of Toplis and Harte would have been welcome. Still later, Mary Somerville's acclaimed *Mechanism of the Heavens* [Somerville 1831] gave an accomplished reworking and simplification of much of the *Mécanique céleste*, followed by the American Nathaniel Bowditch's authoritative four-volume translation and detailed commentary [Bowditch 1829–39].

John Toplis's translation of Book 1 was anonymously reviewed in the *Monthly Review*, the writer perhaps being Robert Woodhouse or Peter Barlow [[Anon. (R. Woodhouse or P. Barlow?)] 1815]. The reviewer not only shared Toplis's gloomy view of the state of British mathematical science, but feared that the book would have few readers:

> We are under the painful necessity of admitting that, on the Continent, during the last half century, the mathematical sciences, and particularly the analytical branches of them, have been pursued with an ardour and constancy that insured success, while scarcely any improvement has been made in them in England; although this may be considered as the county of their birth. So far, indeed, are we behind our continental neighbours, that many of our medium-mathematicians would be unable to peruse a hundred pages of the important work of which we have here in part a translation, without some such aid as they will find in the notes to the present volume...
>
> On the whole, therefore, Mr. Toplis has rendered an essential service to English students, by enabling them to commence the study of one of the most important works that any age or country has ever produced, if we except the "*Principia*" of our illustrious Newton; and we sincerely hope that it may meet with the encouragement which it deserves, though we must add that in this respect our doubts exceed our hopes. A mathematical production, above the level of school-practitioners, finds little encouragement in this country; to enable a book to sell, it must be trifling; it must reduce all rules to mere mechanical operations; it must in fact be suited to the taste of *solvers of problems*, and not to *investigators*:—we have more of the former class, and fewer of the latter, than any empire in Europe.

Reviews of several of Laplace's works by Playfair and Woodhouse are described below. [18]

Playfair concluded his 1808 review of Laplace's *Mécanique céleste* with an often-quoted passage [[Playfair] 1808], [1822, **4**, 323-324]:

> ... a man may be perfectly acquainted with every thing on mathematical learning that has been written in this country, and may yet find himself stopped

18 On Laplace and his many publications, see [Gillispie 1997], [Grattan-Guinness 1990].

> at the first page of the works of Euler or D'Alembert… from want of knowing the principles and the methods which they take for granted… If we come to works of still greater difficulty, such as the Mécanique Céleste, we will venture to say, that the number of those in this island, who can read that work with any tolerable facility is small indeed. If we reckon two or three in London, and the military schools in its vicinity, the same number at each of the two English Universities, and perhaps four in Scotland, we shall not hardly exceed a dozen; and yet we are fully persuaded that our reckoning is beyond the truth.

He suggests that the two English Universities and the Royal Society [of London] must bear much of the blame for their insufficient encouragement of mathematical learning. Though Playfair's view had much merit, it was not well received by these institutions. From Oxford, for example, a detailed response defending traditional education was given by Edward Copleston [[Copleston] 1810]: see also [Fauvel 2000, 166], [Ackerberg-Hastings 2008]. But, though that university had produced several distinguished observational astronomers, notably James Bradley and Thomas Hornsby, Oxford mathematics was certainly backward and conservative [Fauvel 2000]. Among its professors of mathematics and natural philosophy around this time, Baden Powell (1796-1860) was the best of an undistinguished bunch. [19]

Table 1 lists some of those born during 1750-1790 whom Playfair may have thought capable of appreciating the work of Laplace and other French savants. Their places of education and occupations are shown. Information on many can be found in [Guicciardini 1989], the *Oxford Dictionary of National Biography*, the online St Andrews MacTutor History Archive http://www-history.mcs.st-andrews.ac.uk/history/Biographies/ and Wikipedia. Further references are shown in the Table. All of these individuals are mentioned above or below.

From among these, we first single out Robert Woodhouse, some of whose reviews feature below. He was a student, Senior Wrangler of his year, and then a fellow of Caius College, Cambridge. Woodhouse was influenced by Edward Waring's analytical writings, notably his *Miscellanea Analytica* [Waring 1762]. He probably also knew Waring's successor, Isaac Milner. Woodhouse was briefly Lucasian Professor of Mathematics during 1820-22, before becoming the Plumian Professor of Astronomy and Experimental Philosophy. He was involved in the campaign for and construction

[19] Baden Powell privately admitted his "want of command of analysis," and is remembered less for mathematics than for his optical researches and for his progressive views on science and theology [Corsi 2004].

TABLE 1.

John Bonnycastle (1751-1821)	Bucks	RMA
John West (1756-1817)	StAU	priest, Jamaica [Craik 1998]
John Brinkley (c.1763-1835)	CU	DU [McConnell 1944], [Grattan-Guinness 1988]
James Ivory (1765-1842)	StAU, EU	RMC [Craik 2000b], [2002]
John Leslie (1766-1832)	StAU, EU	EU [Napier 1837], [Olson 1975], [Craik 2000a]
John Pond (1767-1836)	CU	Astronomer Royal [Murray 2004]
William Wallace (1768-1843)	EU	RMC, EU [Panteki 1987], [Craik 1999], [2000a]
Bartholomew Lloyd (1772–1837)	DU	DU [McConnell 1944], [Grattan-Guinness 1988]
Robert Woodhouse (1773-1827)	CU	CU [Becher 1980b], [Phillips 2006]
Thomas Young (1773-1829)	EU, CU	medic, writer [Robinson 2006], [Craik 2010a]
John Toplis (1774-1857)	CU	headmaster, CU, priest [Cannell 2001]
Thomas Knight (1775-1853)	EU	private [Craik & Edwards 2004], [Craik 2013b]
Peter Barlow (1776-1862)	Norwich	RMA
William Spence (1777-1815)	Greenock	private [Craik 2013a]
Henry Brougham (1778-1868)	EU	law, politics [Brougham & Vaux 1872–73]
Mary Somerville (1780-1872)	Edin, Lond	writer [Patterson 1983], [Chapman 2004]
James Thomson (1786-1849)	GU	BC, GU [Smith & Wise 1989]
John Herapath (1790-1868)	Bristol	writer, journalist [Truesdell 1968], [Brush 1973]
Henry Harte (1790-1848)	DU	DU [McConnell 1944], [Grattan-Guinness 1987], [1988]

Abbreviations: BC = Belfast College, CU = Cambridge University, DU = Dublin University, EU = Edinburgh University, GU = Glasgow University, RMA = Royal Military Academy, Woolwich, RMC = Royal Military College, Marlow then Sandhurst, StAU = St Andrews University, Bucks = Buckinghamshire, Edin = Edinburgh, Lond = London.

of the University's observatory, and he became its first director [Becher 1980b], [2004].

In 1803 he published *The Principles of Analytic Calculation*, and in 1810 *A Treatise on Isoperimetrical Problems and the Calculus of Variations* [Woodhouse 1803], [1810], both subsidised by the Syndics of Cambridge University

Press. Much influenced by Lagrange, they addressed advanced analytical topics and so were at first read by few. Woodhouse's other works, *A Treatise on Plane and Spherical Trigonometry* (1809), *An Elementary Treatise on Astronomy* (1812; 1818), and *A Treatise on Astronomy Theoretical and Practical* (1821-23), were designed for students and were more read. The first volume of [Woodhouse 1812/1818] is devoted to practical observational astronomy, with just a few French references. The second volume of 1818, devoted to "Physical Astronomy," begins with a long historical Preface that extols Lagrange and Laplace, who "belong to the second list of Newton's successors: but amongst the whole list of those successors there are no brighter names" [1812/1818, vol. 2, *xlviii-lvii*]. The whole second volume is written at a far higher mathematical level than the first, drawing on much from Laplace's *Mécanique céleste* and elsewhere. This volume was again substantially subsidised by the Syndics of Cambridge University Press. The later *A Treatise on Astronomy Theoretical and Practical* (1821-23) is a reworked second edition, covering similar ground. Only six papers by Woodhouse are listed in the *Royal Society Catalogue of Scientific Papers 1800-1900*: four mathematical ones during 1801-1804 and two on astronomical transit instruments in 1825-27. A comprehensive discussion of Woodhouse's career, books and papers is in [Phillips 2006]. Woodhouse's many reviews for the *Monthly Review*, mostly written between 1798 and 1809, have escaped the notice of most historians, and are discussed below.[20]

John Brinkley became Andrews Professor of Astronomy at Dublin University. His *Elements of Plane Astronomy* [Brinkley 1808] (this first edition now elusive) was, after [Vince 1797–1808] and [Gregory 1803], the next English-language university textbook devoted exclusively to astronomy; but [Robison 1804] also has a considerable section on physical astronomy. This and his subsequent *Elements of Astronomy* [Brinkley 1813] were republished in several later editions, some edited by a former student, Thomas Luby (1800-1870), who himself published a substantial *An Introductory Treatise to Physical Astronomy* [Luby 1828]. Brinkley clearly had a good knowledge of continental mathematics, and published many papers on astronomical and mathematical topics in the early volumes of the *Transactions of the Irish Academy*. He has high praise for Lagrange and Laplace: the latter's ""Mechanique Celeste" [with] the Principia of Newton will probably be considered by late posterity as the two noblest monuments of human science." [Brinkley 1813, p. 282 of 2nd edn. 1819]. As he went

20 These are mentioned only very briefly in [Phillips 2006].

on to become the Bishop of Cloyne of the Episcopal Church of Ireland, it is unsurprising that, like Robison and Playfair, he devotes his concluding remarks to the perceived evidence of a Divine Creator in the wonderful structure revealed by astronomy.

The reform of mathematical teaching in Dublin University was accomplished by Bartholomew Lloyd following his appointment as Professor of Mathematics in 1812. This is vividly described in [McConnell 1944, 76-77]:

> The foundation of the École polytechnique at the end of the century brought together as its professors the most brilliant mathematicians of the day, Lagrange, Laplace, Poisson, Fourier, Monge, Legendre, and a series of excellent text-books based upon their lectures began to appear. These found their way to Dublin and Cambridge, and the more progressive spirits realised that things could no longer continue as they were. In Dublin one man alone, Bartholomew Lloyd, conceived and executed the most important and rapid revolution ever effected in the academic studies of a university. The French text-books were introduced into the courses and new ones were written to meet the demand for instruction in the continental methods.

Lloyd transferred to the chair of Natural and Experimental Philosophy in 1822, and in 1831 was elected provost of the college. In this latter post, he instituted many enlightened reforms: see [Hamilton 2004] and references therein. [21]

Also deserving mention is James Thomson, appointed in 1814 to the newly-opened Belfast Academical Institution and later professor of mathematics at Glasgow University. He wrote several textbooks, among them *The Differential and Integral Calculus* [Thomson 1831]. More importantly, he fostered the education and careers of his two eldest sons, the engineer James and the physicist William (Lord Kelvin) [Smith & Wise 1989].

John West was an assistant to the ailing Nicolas Vilant at St Andrews, and taught both James Ivory and John Leslie. Though he published a worthy *Elements of Mathematics, for the Use of Schools* [West 1784], this failed to improve his prospects. Accordingly, he emigrated to Jamaica and trained

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21 In the following decades, a strong Irish school developed in mathematics and its applications: the most illustrious of these scholars were Humphrey Lloyd (son of Bartholomew), William Rowan Hamilton, James MacCullagh, and George Salmon, who fall outside the period of this study: see e.g. [McConnell 1944], [Grattan-Guinness 1988], [Flood 2011]. So too does the English-born mathematician and logician George Boole, who had studied works by Lacroix, Laplace and Lagrange, and had close contacts with some Cambridge algebraists: in 1849 he became Professor of Mathematics at Queen's College, Cork [MacHale 1985], [Durand-Richard 2004]. Two other able Irish-born mathematicians and physicists, Robert Murphy (1806-1843) and Matthew O'Brien (1814-1855), were both Cambridge-educated and did all their work in Cambridge and London: see [Crilly 2004b], [Smith 2004].

as an Anglican priest (licensed to officiate only in the colonies). He published nothing more, but left many manuscripts, eventually issued, far too late, as *Mathematical Treatises, Containing I. The Theory of Analytic Functions, II. Spherical Trigonometry, with Practical and Nautical Astronomy... edited... by the late Sir John Leslie* (in fact, by Edward Sang) [West 1838]. These show familiarity with work of Lagrange, Laplace and Arbogast. Probably all written before 1810, West's *Treatises* might have served as one of the first English-language textbooks of calculus and its applications, had they been published promptly. In more advantageous circumstances, West might have become one of the leading British mathematicians of his day [Craik 1998].

Though a fine mathematician, William Spence was, like John West, an isolated figure. He grew up in Greenock, near Glasgow, and attended no university. Without any paid occupation, he pursued his private researches. But for his friendship with the writer John Galt, he might well have disappeared from view. His publications [Spence 1809] and [Spence 1814/1817] had very small print-runs. Following Spence's early death, John Herschel edited his unpublished manuscripts and reprinted the above works as *Mathematical Essays* [Spence 1819], with a biographical memoir by Galt. Unfortunately, copies became hard to find, and Spence's work was for long known to just a few.[22] According to Herschel, Spence "appears to have studied entirely without assistance, and to have formed his taste and strengthened his powers by a diligent perusal of the continental models. In consequence, he was enabled to attack questions which none of his countrymen had entered upon..." [[Herschel] 1832]. (Spence mentions works by Euler, Landen, Lorgna, l'Huillier, Ferroni, Laplace, Legendre, Lacroix and others.)

One of few to comment on Spence's work was the gentleman amateur Thomas Knight of Papcastle in Cumbria. He published a number of analytical papers during 1809-18 in the *Philosophical Transactions of the Royal Society of London* and in Leybourn's *Mathematical Repository*. Like West, he too attempted a reworking of Arbogast's *Calcul des derivations*, but his notation is repellent. His mathematical background is obscure, but he seems to have been influenced by Playfair when briefly studying medicine in Edinburgh, and he had certainly read works of Laplace, Lacroix and Legendre as well

22 See [Craik 2013a]. A further short article in the *Philosophical Magazine* [["W.S." (William Spence)] 1808], surely by William Spence, but omitted from [Spence 1819] and overlooked by [Craik 2013a], demonstrates how Taylor's theorem can be used to derive several key results in analysis.

as Arbogast. But he received more criticism than praise, and gave up mathematics around 1820 to concentrate on his estate and large family [Craik & Edwards 2004], [Craik 2013b].

Between 1816 and 1835, another outsider, John Herapath, published twenty-two papers (and some more under pseudonyms), mainly in *Annals of Philosophy* and the *Philosophical Magazine.* There are mathematical ones on functional equations, differential equations, and the binomial theorem; and several on aspects of physics, especially heat and the properties of gases. Two papers comment on publications of Laplace and Lagrange. In neglected work of 1816 and 1821 he partly anticipated the kinetic theory of gases. Offended by rejection of his papers by the Royal Society, his writings became increasingly polemical. That he was unfairly dealt with, on account of ignorance and prejudice at the Royal Society, is argued by [Truesdell 1968, 283-288]: but see [Brush 1973] and [Hutchison 2004]. A late work [Herapath 1847] contains much on the physical properties of gases; but today Herapath is perhaps better known as founder and editor of the world's first railway magazine.

At the Royal Military College, Great Marlow (later Sandhurst), both William Wallace and James Ivory were early supporters of the "continental" notation, using the College's *Mathematical Repository* to promote its use. The *Mathematical Repository*, edited by Thomas Leybourn, was mostly written by Royal Military College staff, often using pseudonyms. It was the most mathematically ambitious of several popular magazines that offered articles, news, and problems for readers to solve: see [Guicciardini 1989, 115-117], [Craik 1999], [Despeaux 2011], [Albree & Brown 2009]. Wallace also wrote for *Encyclopaedia Britannica*, including articles on "Conic Sections" and "Fluxions," respectively later translated into Russian and Chinese.

For the rival *Edinburgh Encyclopaedia*, Wallace's 85-page article was misleadingly also entitled "Fluxions" [Wallace 1815] as he missed the publisher's deadline for "Calculus". As already mentioned, this was the first complete account in English of the differential and integral calculus to use "continental" notation. In it, he based the calculus on the "doctrine of limits," which brought a misguided complaint from the young John Herschel [Craik 1999].

Wallace's later books were more mundane texts on trigonometry and geometry; but he rightly felt aggrieved that his early work on calculus was overlooked in an 1833 review by George Peacock [Panteki 1987]. As Professor of Mathematics in Edinburgh, along with his routine teaching, he championed the refurbishment of the Calton Hill Observatory with advice from William Herschel, and he designed and had constructed novel instruments for copying and surveying [Craik 1999], [2010a].

James Ivory, like Wallace, contributed to the *Mathematical Repository* (sometimes under pseudonyms) and wrote articles for *Encyclopaedia Britannica Suppl.,* [Ivory 1815], [1820]: one, on capillary attraction, favoured Laplace's account over that of Thomas Young, to the latter's displeasure. For the *Repository*, he gave an early (anonymous) rederivation of Gauss's discovery on the constructability of regular polygons within a circle, perhaps derived from Legendre's demonstration [[Ivory] 1803].[23]

Ivory retired early from the Royal Military College in 1817 with unstable mental health, and he lived the rest of his life in London, in modest and socially-isolated circumstances. Yet he was undoubtedly Britain's most distinguished applied mathematician, honoured by the award of three medals by the Royal Society of London, and of a Guelphic knighthood by the King and Government. He was also a foreign member of several European scientific societies, including the Institut de France.

Ivory's main contributions were his researches on the theory of gravitational attraction and the "figure of the Earth," in which he made some improvements to the work of Laplace in the *Mécanique céleste*. Among these were "Ivory's theorem," an important result concerning the gravitational attraction of solid ellipsoids, and some other clarifications. Ivory's result was said to "produce a great sensation among the members of the Académie des Sciences of Paris" [Grattan-Guinness 1990, 418], and Laplace briefly acknowledged Ivory's work in later editions of his *Mécanique céleste*. Unfortunately, Ivory became obsessed with this problem, producing many more papers, a few of some originality, some merely polemical and others incorrect.[24] He notably quarrelled with Poisson during 1824-27 over his mistaken idea that a new condition should be added to the accepted equations of hydrostatics governing a rotating self-gravitating fluid mass: see [Grattan-Guinness 1990, 1190-95].

Ivory's papers on the calculation of tables of atmospheric refraction for use in astronomy were also acclaimed in his day: it was primarily for these that he received two Royal medals from the Royal Society. He derived these tables on the basis of certain assumptions concerning the variation of air temperature with atmospheric height, claiming better agreement

23 A similar proof is given by John West, who could have seen the *Repository*, or met Ivory, during a visit to England in 1803 [Craik 1998].

24 Many appeared in the *Philosophical Magazine*, which encouraged controversies: between 1821 and 1830, Ivory there published sixty-two articles on a variety of topics under his own name, and several more under pseudonyms.

with observation than the Nautical Almanac tables. Other work concerned Legendre functions that arise in the theory of the figure of the Earth [25], and the motion of pendulums for use in geodesy. More minor publications concerned topics such as the "elastic force of steam" at different temperatures, potentially applicable to steam engines. More details are in [Craik 2000a], [2002].

Mary Fairfax (Greig) Somerville was born in Burntisland, Scotland and subsequently lived in Edinburgh, London and Italy. A vivid account of her varied life, written by herself and edited by a daughter [Somerville & Somerville 1873/1874], reveals the extent of her scientific contacts. She has been the subject of several biographical studies [Patterson 1983], [Neeley 2001], [Chapman 2004]; and there is a nine-volume edition of her collected works [Somerville & Secord 2004].

One of her first contacts was William Wallace, who exchanged solutions of *Mathematical Repository* problems with her: she was pleased to win a silver medal for the best solution to the "Prize Problem" of 1811. Advised by Wallace, she purchased works by Francoeur, Lacroix, Biot, Poisson, Lagrange, Euler, Clairaut, Monge, Callet, and Laplace, and "could hardly believe that she possessed such a treasure" [Somerville & Somerville 1873/1874, 79].

Though she and her family were never rich, they were socially well connected, and Mary's accomplishments gave her ready entry into scientific and literary society. She met luminaries of the Whig *Edinburgh Review*, including Henry Brougham, John Playfair, Sydney Smith and John Leslie. She engaged John Wallace, William's brother and himself a good mathematician, to discuss the *Mécanique céleste*, but "soon found that she understood the subject as well as he did" (p. 82, 91). Mary and her family moved to London in 1816 and quickly became known to London's scientific society: they attended lectures at the Royal Institution and visited the Herschels at Slough, where they met William's son John, "quite a youth," who became "my dear friend for many years" (p. 106). Other scientific friends included Charles Babbage and Thomas Young.

Mary's first meeting with French scientists occurred in 1817, when "MM. Arago and Biot came to England to continue the French arc of the meridian through Great Britain... They had been told of my turn for science and that I had read the works of La Place" (p. 107). Soon afterwards, the Somervilles stopped in Paris on their way to Switzerland, where they were welcomed by Arago and Biot, and introduced to Laplace, Poisson, Humboldt, Cuvier and others. Of the various British scientists who met Laplace

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25 In this, he independently rediscovered the result called "Rodrigues' theorem".

and other French savants, Mary Somerville is the one who recorded the most vivid descriptions (p. 108-113).

In 1827, she received a request from Lord Henry Brougham (proposed, with customary propriety, in a letter to her husband), to write an account of the *Mécanique céleste* for the "Society for Diffusing Useful Knowledge" (p. 162-163). As her manuscript grew beyond the size of SDUK treatises, it was published separately as *Mechanism of the Heavens* [Somerville 1831]. In 1830, John Herschel wrote to her: "What a pity that La Place has not lived to see this illustration of his great work!" (p. 167). Complimentary copies were warmly acknowledged by William Whewell and George Peacock in Cambridge, who promised "to introduce it into the course of our studies" (p. 172). As a result, the majority of the edition's 750 copies were sold in Cambridge. A separate printing was made of the Preliminary Dissertation: "the only part… that was intelligible to the general reader."

Several honours followed, including a flattering report for the Académie des Sciences in Paris, and an equally flattering letter to her, from her old acquaintance Jean-Baptiste Biot (p. 174). The award of a civil pension by the Government improved the Somervilles' sometimes precarious finances.

On making a further visit to Paris in 1832-33, she met old acquaintances and some new ones, including Pontécoulant, Lacroix, Prony, Poinsot and the Gay Lussacs. Poisson complimented her on *Mechanism of the Heavens* and urged her to write a second volume to complete her account of Laplace's works. She records that "he afterwards told [her husband] Somerville, that there were not twenty men in France who could read my book" (p. 185): a nice, if unconscious, reversal of Playfair's complaint about the small number of British scientists able to read Laplace!

Poisson had urged her to write on "the form and rotation of the earth and planets" that she had not covered in the *Mechanism of the Heavens*, but which was treated by Laplace and others. On her return, she began work, corresponding with James Ivory and Francis Baily. In her own words, "My work was extensive, for it comprised the analytical attraction of spheroids, the form and rotation of the earth, the tides of the ocean and atmosphere, and small undulations." This, and a slightly later work "of 246 pages on curves and surfaces of the second and higher orders" were never published, but survive in manuscript in Oxford's Bodleian Library (p. 202).

Her other major publications, of which the first two had great popular success, were *On the Connexion of the Physical Sciences* [Somerville 1834], *Physical Geography* [Somerville 1849], and *On Molecular and Microscopic Science* [Somerville 1869]. These books, far less technical than *Mechanism of the Heavens*, were among the first truly popular works of what is now called "popular science"; but, more than that, they aspired to interpret and contextualise the most recent scientific discoveries. Her fame as a woman who had attained eminence in a man's world doubtless contributed to the popularity of her works; but more important was her wide-ranging knowledge and gift for clear exposition.

About one third of *Connexions* consists of a revised version of the long Preliminary Dissertation in *Mechanism of the Heavens*, the remainder comprising sections on sound, light, heat, electricity and magnetism. Among many favourable reviews was that in *The Athenaeum*, by the prolific writer and historian William Cooke Taylor, who described it (in unconsciously sexist terms) as "a most delightful volume… at the same time a fit companion for the philosopher in his study, and for the literary lady in her boudoir…" [[Taylor] 1834] [26]. It is also noteworthy that John Couch Adams acknowledged that the initial impetus for his search for the planet Neptune came from a suggestion in the sixth 1842 edition of *Connexions*, in which Mary Somerville wrote that

> If, after a lapse of years, the tables formed from a combination of numerous observations should be still inadequate to represent the motions of Uranus, the discrepancies may reveal the existence, nay, even the mass and orbit, of a body placed for ever beyond the sphere of vision. [27]

After the defeat of Napoleon in 1815, there were regular visits to Britain by French scholars, and to France by British ones. Even before the war ended, John Leslie had visited Holland and France in 1814, when he met Laplace and Alexander Humboldt; and John Playfair was another to travel again to the continent, making a seventeen-month and four-thousand-mile journey through France, Switzerland and Italy. His main aim was geological, but he spent six weeks in Paris, where he appreciated "the flattering reception and kind attention he experienced from the literary and scientific society of Paris." [Playfair 1822, 1, p. xxviii]. Biot and Arago were among the earliest French visitors, in 1817, when Biot travelled the

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[26] The authors of reviews in *The Athenaeum*, all anonymous, are recorded on the Web site `http://athenaeum.soi.city.ac.uk/reviews/home.html`, which is based on the editor's annotations. I am grateful to Adrian Rice for this information.

[27] I am grateful to Edmund Robertson for drawing my attention to this passage. Adams' admission to William Somerville is mentioned in [Chapman 2004, p. 91].

length of Britain to make pendulum measurements of the Earth's gravity. Through such contacts, mutual interests in physics, astronomy and mathematics were fostered. As other examples, one need only mention that Arago and Thomas Young exchanged visits in 1816-17 to discuss their, and Fresnel's, theories of optics; that Mary Somerville visited Arago, Biot, Laplace and others in 1817 and 1832, and that Herschel and Babbage visited Paris together in 1821, meeting Arago, Laplace, Biot and Alexander Humboldt [Crosland & Smith 1978, p. 41], [Somerville & Somerville 1873/1874].

5. THE REVIEWS OF JOHN PLAYFAIR

John Playfair published many essay reviews in the *Edinburgh Review* during 1803-1818. Exactly how many is uncertain, for all reviews were published anonymously: but compilation of several lists and annotated copies (sometimes contradictory) by [Schneider et al. 1945], [Griggs et al. 1946] and [Houghton 1966–1989, vols.1, 5] has established a fairly full picture. Griggs, Kern & Schneider attribute twenty-four reviews to Playfair during 1802-1812 and Houghton lists fifty-one as certainly or probably by Playfair (and a further nine possibles) during 1802-1818. Just eight are republished in [Playfair 1822, vol. 4]. Here, we focus mainly on those concerning French, and some British, mathematics and astronomy. Several of these reviews are also noted by [Ackerberg-Hastings 2002, 51n] without comment, and by [Ackerberg-Hastings 2008], who discusses several. Presumably in line with editorial policy, Playfair never uses any mathematical symbols or equations in his reviews, and writes throughout in elegant expansive prose.

John Playfair's well-known essay review of Laplace's *Traité de mécanique céleste* [[Playfair] 1808] first outlines the history of mathematical astronomy that formed the background to Laplace's work; and he then gives a well-informed and highly-favourable summary of the ten books of *Mécanique céleste* that had by then been published.[28] He makes it clear that the *Mécanique céleste* is a work of synthesis, incorporating much that was already known from previous analyses by Euler, D'Alembert, Clairaut, Lagrange and particularly Laplace himself, as well as adding new material.

[28] As early as 1790, Playfair had mentioned articles by Lagrange and Laplace within a long article "Remarks on the Astronomy of the Brahmins" [Playfair 1790]. Of his *Edinburgh Review* essays, those *not* reprinted in [Playfair 1822] are cited with his name in square brackets.

Among Laplace's major results were improved calculations of the perturbations of the orbits of the Moon, Jupiter, Saturn and the other planets; investigation of Saturn's moons; an estimate of the oblate "figure of the Earth" and its influence on the Moon's orbit; a theory of oceanic tides; and estimates of astronomical refraction of light.

In some final reflections, Playfair commends Laplace's success in theoretically establishing the stability of the solar system, a fact which Playfair claims "is the effect of wise design exercised in the construction of the universe".[29] Thus "the discoveries of Lagrange and Laplace lead to a very beautiful extension of the doctrine of *final causes*… This is not taken notice of by Laplace; and that it is not, is the only blemish… in his admirable work." [Playfair 1822, **4**, 318-9]. Clearly, such religio-philosophical conjectures still lay within the scope of Scottish natural philosophy.[30] (Robert Woodhouse's several reviews of the *Mécanique céleste* are discussed below.)

Two years later, Playfair reviewed John Pond's English translation of Laplace's *Exposition du système du monde* [[Playfair] 1810b], made by one "fully capable of understanding and valuing the discoveries of his author" (p. 416). He praises this "brief but clear and accurate account of the phenomena of the heavens" that Laplace had treated in fuller detail in "his great work of the Méchanique Céleste"; this non-technical abridgement is "of infinite value, even to the most profound mathematician" (p. 399).[31] Playfair gives many lengthy quotations from the translation, and mentions that Biot had written an "Introduction to Physical Astronomy" based on the first two of Laplace's chapters. Finally, he deplores a recent pamphlet attacking Laplace's theory of capillary action, objecting to its bad taste, petulance, and insolent tone (p. 417). Though Thomas Young crossed swords with Laplace on this topic, the culprit to whom Playfair refers is probably Thomas Knight, whose privately-printed polemical pamphlet [[Knight] 1809] appeared at this time.

Even more interesting is Playfair's preamble, in which he confronts a debate that still rages today: should science be directed towards utility, or should it be curiosity-driven? Playfair approaches the question in the light of the French revolution, when much effort was expended by leading

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29 As recently discovered, Laplace's demonstration of stability, built on previous work of Lagrange, was flawed: see [Laskar 1995a], [1995b], whose computations indicate that the inner planets have chaotic orbits over an exceedingly long time scale.

30 See [Durand-Richard 2012, p. 4-5]. Also, [Rice & Seneta 2005] discuss the use of probability theory by Augustus De Morgan to attempt to show that the fact that all planets orbit in the same sense around the sun could not result from mere chance.

31 In fact, *Exposition du système du monde* was first published in 1796, three years before the first volume of the *Mécanique céleste.*

mathematical scientists in composing elementary and popular works "to connect their favourite studies with objects of manifest utility". However,

> an endeavour to keep up a constant and immediate connexion between the researches of science and the uses of life, is by no means likely to have at all times the same salutary effects… The sciences must often be cultivated from the mere feeling of their own excellence, and must be followed into recesses where their immediate connexion with objects of utility cannot be perceived. (p. 397)

As examples, he cites lunar theory, without which the eventual calculation of longitude could not have been achieved; and John Napier's computation of logarithmic tables to facilitate arithmetic, in ignorance of their many later uses. "To foretel [sic], beforehand, the uses to which a discovery, whether mathematical or physical, may be applied, is not given to man… There is a great danger to science, therefore, from keeping utility too closely in view, and thus hampering a progress that should be free and unconfined." (p. 398).

The third volume of Vince's *A Complete System of Astronomy* [Vince 1797–1808], published in 1808, was devoted entirely to solar, lunar, planetary and other tables deduced using Laplace's theories. After describing the formulae on which these were based (but without derivations), Vince presents 244 pages of tables, describing perturbations of the orbits of the Moon, of all the known planets, the moons of Jupiter, atmospheric refraction and aberration of light. In a little-known review of this, anonymous but certainly by Playfair, the author comments [[Playfair] 1809, 80]:

> The observations of Bradley and Maskelyne, have afforded the only *data* sufficiently correct to enter into the calculus of La Place and De Lambre. It is satisfactory to see this merit so well stated and so candidly acknowledged in the letter above quoted.[32] Notwithstanding the spirit of hostility that has so long animated England and France against one another, it is comfortable to think that there are a few men in each, impartial enough to do justice to the merits of one another.

The reviewer commends the tables for their accuracy, but regrets "that no preface or advertisement announces… what is the exact share which Mr Vince himself claims in the work which he has given to the world." He notes that most of the tables are the work of Bürg and Delambre (though somewhat rearranged), but that: "We are left in an uncertainty with respect to the tables of Mercury, Venus and Mars; or rather, as nothing is said to

32 The letter in question, from Delambre to Maskelyne, dated 20 February 1806, quoted in full on p. 63 of this review, accompanied the gift of six copies of Bürg's lunar tables. Delambre expressed the hope that they would be used in the calculations for the *Nautical Almanac.*

the contrary, we are to consider them as drawn up by Mr Vince himself" [[Playfair] 1809, 65]. Elsewhere, Playfair noted that, rather than "Vince's Astronomy" the title of this volume ought to have been "Vince's edition of the Tables of Burg and Delambre" [[Playfair] 1809, 352].

Vince's tables received more severe criticism in an anonymous 1825 review, identified as by Nathaniel Bowditch [[Bowditch] 1825]. This extensive review, ostensibly of several sets of astronomical tables, is virtually a history of astronomy, both theoretical and practical. Of Vince's tables he writes:

> The 'Complete System of Astronomy,' by Professor Vince, in 3 vols, contains much useful matter, but it must be acknowledged, that it bears many marks of a crude compilation, particularly in the tables...; being copied from the works of La Lande, Delambre, and Burg, without taking the trouble to make much alteration, except in adapting them to the meridian of Greenwich. This mixture of different forms and systems... may frequently lead to error... [[Bowditch] 1825, 359]

The lunar tables were intended for use in determining longitude at sea, and Playfair expressed satisfaction that they now possessed a "degree of accuracy fully sufficient for all the purposes of navigation." Thus, "The irregularities which so long obstructed the science of astronomy, have been the principle means of its advancement." [[Playfair] 1809, 71]. But the cumbersome astronomical-table approach to navigation was soon superseded by the use of accurate marine chronometers, following the pioneering inventions of John Harrison. [33] A further review of Vince's work by Robert Woodhouse is mentioned below.

Among other essays by Playfair are his 1809 "Review of le Compte Rendu par l'Institut de France" and his 1814 "Review of Laplace, Essai Philosophique sur les Probabilités." [34]

In the first, which summarises Delambre's report (later published separately as [Delambre 1810]), he praises Legendre's *Géométrie* [Legendre 1802] for its novel analytical treatment of "the properties of parallel lines, without assuming any new axiom" [Playfair 1822, 337]. Likewise, the geometrical "Elements of Lacroix are also extremely valuable, though not

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33 John Robison, an ex-Navy man, was involved with the latter, having taken part as official Board of Longitude representative, along with Harrison's son William, in a long voyage to Jamaica and back in 1761-62, to test Harrison's H-4 chronometer [Sobel 1996, 120-121].

34 The *Essai,* the introduction to [Laplace 1812], first appeared separately in 1814. Both reviews are republished in [Playfair 1822], to which we give page references below.

marked, so strongly as [Legendre], with the characters of originality and invention" [Playfair 1822, 339]. After commenting at some length on Delambre's review of other recent work, he commends Lagrange's recent "Calcul des Fonctions, intended as a commentary and supplement to the Théorie de Fonctions Analytique" for students at the "Polytechnic school" (i.e., the École polytechnique). He particularly admires Lagrange's approach whereby "the differential calculus is reduced to the algebra of variable but finite quantities," without invoking "evanescent quantities" as Euler and most others had done [Playfair 1822, 347-349]. He also mentions "a work of great merit… but little known in this country," Lagrange's *Traité de la resolution des equations numérique de tous les degrees*, "though the memoir which is the foundation of it was published by Lagrange so long ago as the year 1767" [Playfair 1822, 350]. Finally, he again mentions Laplace's *Mécanique céleste*, "on which … too much praise cannot be bestowed" but which he has discussed elsewhere. The remainder of Playfair's essay goes on to describe other advances in physical and chemical sciences.

In his 1814 review of Laplace's *Essai philosophique sur les probabilités*, Playfair mentions previous studies by Fermat, Pascal, Huyghens, Jakob Bernoulli, De Moivre and others, and remarks that Laplace has made "some valuable improvements": most notably, the calculus of Generating Functions, of which Laplace first explained the principles in a paper of 1779 [Playfair 1822, 430]. Playfair does not enter into technicalities, but rather discusses at length the many areas in which the theory of probability can be applied. He emphasises that minimising the sum of squares of deviations gives the best estimate of a mean value.

Playfair's commendation of Legendre's *Géométrie*, in which the parallel postulate was replaced by an analytical demonstration employing dimensional analysis, was not supported by John Leslie. Leslie published his objection in his own geometry textbook [Leslie 1809] (unfavourably reviewed in [[Playfair] 1812]) and repeated his ill-founded remarks in later editions. This eventually brought a strong reply from Legendre himself in the English translation of his work, made by Thomas Carlyle at the behest of David Brewster (an arch-rival of Leslie) [Legendre 1824]. A considerable correspondence followed in the *Philosophical Magazine*. The matter was finally resolved by James Ivory, who pointed out that Legendre's analytical version, rather than eliminating the parallel postulate, contained an assumption equivalent to it: see [Craik 2000a].

The review [[Playfair] 1811] addresses Ivory's important paper "On the [gravitational] attraction of homogeneous ellipsoids" [Ivory 1809]. After a full account of the long history of the problem up to Laplace, Playfair attempts "to convey in words the idea of [Ivory's] algebraic investigation" (p. 487). In summary, "The author appears to be profoundly versed in the most difficult parts of [analytical] science, and in those recent improvements that do so much honour to the mathematicians of the Continent. He has made a material addition to those improvements; and is entitled to the praise of having given new simplicity to an investigation which had passed through the hands of D'Alembert, La Grange and La Place." (p. 488).

A scathing review of Dealtry's *Principles of Fluxions* [[Playfair?] 1816] (or perhaps by Henry Brougham) criticises the many defects of this work: imprecise handling of foundations; apparent ignorance of Lagrange's "purely algebraic" formulation of calculus, free of infinitely small quantities and of the Newtonian concept of motion; and various important omissions. Only the last long chapter of miscellaneous examples is praised. (In fact, much of this is culled from Vince's *Fluxions.*) The student "will find himself sadly disappointed; … after being a perfect master of all that is contained in this treatise, he will not find himself prepared for reading the first six pages of the *Mechanique Celeste*" (p. 98).

Far more complimentary is a very full review of Woodhouse's *Trigonometry.* [[Playfair] 1810a]. Both plane and spherical trigonometry are treated, including Legendre's work on spherical triangles. In summary, "Mr. Woodhouse… has long cultivated the profoundest parts of the mathematical sciences, and has done much to turn the attention of his countrymen to subjects that have been far more studied on the continent than in this island." (p. 125).

Some years later, Woodhouse's two-volume *An Elementary Treatise on Astronomy* [Woodhouse 1812/1818] likewise received a favourable review [[Playfair] 1819] [35]. After a historical introduction, the first volume ("Plane Astronomy") is outlined and various corrections are discussed that must be applied to observations to find true position; then volume two ("Physical Astronomy") is described as "admirably adapted to be a stepping-stone to the Méchanique Céleste of La Place" (p. 384). Despite some obscurities, "we cannot but congratulate the country on the appearance of the first work calculated to convey an accurate notion of the methods used in the later and more profound researches of Physical Astronomy; the only methods… by which those researches can be successfully prosecuted…" The main obstacle to its reception is the continuing

35 In [Houghton 1966–1989, vol.1], this review is strangely attributed to the lawyer William Brougham, brother of Henry; but it is later given as Playfair's in the index of volume 5.

absence of suitable books in English: there being "none where the Integration of Fluxionary Equations is delivered with the necessary extension; none in which the method of *Partial Differences* is explained, or where the method of *Variations* is so much as mentioned" (p. 391-392).[36]

The reviewer then considers why Great Britain had contributed so little to recent advances, admitting that reverence for Newton's *Principia* and resistance to continental calculus had played a part. But he suggests other factors: Britain "has done more for Chemistry, than all Europe put together,… given greater encouragement to the arts—to agriculture and manufactures—to literature and general science…" (p. 392). "Now-a-days, a man [of education] must be conversant in chemistry, mineralogy, entomology, modern languages, history, politics, and fifty hard-worded studies beside—so that… unless he chuse [sic] to devote himself almost exclusively to Mathematics, he has little chance of aspiring to discovery, or even eminence, in that pursuit" (p. 393). Unlike the pensions and honours bestowed by the Royal Academy of Paris, "the only inducement to invention or discovery, is the hope that, by making sufficient interest, the Royal Society may be prevailed upon to allow the paper to be read before them" (p. 394).

Returning to Woodhouse: "No man has done so much to improve the studies of Cambridge… His Trigonometry may be said to have introduced the New Calculus into that university. We hope the present work will serve still further to recommend it,—and to make its value known, not to the student only, but also to the Master" (p. 394).

As well as Playfair's opinion of the up-and-coming Woodhouse, it is worth recording his views on Charles Hutton, a fellow elder statesman of British science, as contained in his review of Hutton's *Mathematical Tracts* [Playfair 1813]. Playfair writes warmly that:

> The author of these Tracts has long held a distinguished place among the mathematicians of this country… his progress accordingly has been marked by many original discoveries, and by a constant attention to the utility of the objects he has pursued. Dr. Hutton possesses, besides, extensive reading and an accurate knowledge of the history of Mathematics:– he has of consequence become a popular as well as a profound author, and one of those who, during the last 50 years, have the most contributed to the diffusion of mathematical knowledge in this island.

The several historical tracts, however, would have benefited from "fuller reference to editions, chapters, and pages"; and the long tract on "Algebra" gives too much detail about little-known authors—despite which, he

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36 In fact, these topics are included, though fairly briefly, in the English translation [Lacroix 1816], presumably still unknown to, or forgotten by, the reviewer.

reproduces a lengthy quotation about Robert Recorde that "may be interesting to our readers". He favourably outlines Hutton's work on infinite series; but is less enthusiastic about some geometrical constructions. The latter concern division of a circle, or ellipse, into any number of parts that are equal both in area and in circumference: "we can hardly consider it as a matter of so much importance as it seems to appear to the author of it himself."

He notes a surprising observation by Hutton regarding James Ferguson, the popular lecturer on astronomy and mechanics, who in 1770 allegedly admitted that he had never learned Euclidean geometry, and convinced himself of the truth of theorems by making accurate drawings.

Playfair devotes much space to reviewing Hutton's involvement in Maskelyne's "Schehalien experiment" to determine the deviations of a plumb line due to the mountain's gravitational attraction, and so draw conclusions regarding the Earth's mean density. Playfair, a knowledgeable geologist, commends Hutton's laborious calculations of Schiehallion's attraction based upon a detailed survey of the mountain, but he objects to some assumptions.

He also gives a full description the "series of very valuable experiments in Gunnery" conducted under Hutton's direction, for which Hutton was awarded the Royal Society's gold medal in 1778. But he cannot refrain from suggesting his own improvements to a formula for air resistance.

Finally, we consider a group of papers and reviews concerning imaginary or "impossible" quantities in algebra, which were still considered logically suspect. Playfair had first addressed this topic in [Playfair 1779], suggesting that they revealed useful analogies between properties of circles and hyperbolae, which might then be proved rigorously by other means. Later, [Woodhouse 1801], [1802] claimed that demonstrations using imaginary quantities could be admitted as rigorous within algebra; but this was roundly attacked in the *Edinburgh Review* by Henry Brougham [[Brougham] 1803], who knew Playfair's work, and who claimed that no sound logical argument can ever involve things that do not exist. Still later, Playfair returned to this question, in a review [[Playfair] 1808] of a paper by the little-known French mathematician and theologian Adrien-Quentin Buëe [Buëe 1806].[37]

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[37] The Abbé Adrien-Quentin Buëe (1748-1826) was one of many aristocrats and priests who fled to England from France during and after the French Revolution. He was probably living in Bath when he published this work, but was back in Paris by 1821: see `http://www.minrec.org/libdetail.asp?id=232` (The mineralogical record).

Buëe had proposed that the imaginary quantity $\sqrt{-1}$ be viewed as *perpendicular* to the real lines $+1$ and -1 drawn to right and left from the origin; and that this interpretation permitted entirely logical arguments involving imaginary quantities. Buëe's idea was certainly tenable. Though vaguely expressed, it resembles those published by Jean Argand in the same year, and by Casper Wessel in 1799, both belatedly recognised: see e.g. [Flament 2003], [O'Connor & Robertson 2000]. But Playfair objected that Buëe's principle was "extremely unsound," and that he was "unable to… conceive how a man so learned and ingenious… should have suffered himself for one moment to be deceived by it" (p. 309-310).

In Appendix (a), references and brief comments are given to some other articles in the *Edinburgh Review* that mainly concern mathematics, astronomy and geodesy: most, though perhaps not all, are by Playfair (many more by him on other subjects are not there listed).

Playfair's role in informing a wide readership of the achievements of French mathematics and astronomy, and in commenting on contemporaneous British writers, was an important one. His narrative helped extend to science the "improving" aims of Whig intellectuals, while emphasising the continuing necessity for adherence to rigorous foundations. Though it has been suggested by [Ackerberg-Hastings 2008] that Playfair's reviews were largely responsible for promoting the "myth" of British decline in mathematics at this time, there is strong evidence that the decline was all too real at the research level. The employment of geometrical and fluxional methods could by then rarely rival the power of "continental" analysis, however suspect the latter's logical basis may still have seemed to some.

6. THE REVIEWS OF ROBERT WOODHOUSE

From early in his career, Robert Woodhouse reviewed many works on a wide range of subjects for the London-based periodical, *The Monthly Review, or, Literary Journal.* These seem to be unknown to most historians of mathematics and astronomy. They provide a rich source of information regarding British awareness of current French works, and of Woodhouse's own reading and sometimes-trenchant opinions. Attentive readers of Woodhouse's reviews (if there were such) would have learned a great deal of "continental analysis". A more comprehensive study is warranted; but here attention is restricted to his reviews of several major French, and a couple of English, works. [38]

[38] The *Monthly Review* was edited by Ralph Griffiths and then by his son, George Edward Griffiths. During our period, four volumes were published each year, in twelve

The titles of foreign works reviewed are not given in the indices of [Nangle 1955], and so are not easy to find. Accordingly, some more of Woodhouse's reviews of foreign works are noted in Appendix (b), with a few brief comments. They include Montucla and Lalande's *Histoire des mathématiques*, works by L. Carnot, P.S. Girard, and G. Prony (including the vast unpublished Tables of the *Bureau de cadastre*), and several volumes of papers in Paris and Lisbon periodicals. In one, regarding a paper on the calculus of variations, Woodhouse stated that "We have no great opinion of the mathematical abilities of M. Ampère"; he is also critical of the Portuguese professor G. Stockler's work on the theory of fluxions; and he is unenthusiastic about all of Carnot's books.

Absent from the works reviewed by Woodhouse are Lagrange's *Mécanique analytique* and books by Legendre. (Woodhouse mentions in his review of Gauss that he had not seen Legendre's *Essai sur la théorie des nombres.*) The first edition of Lagrange's *Mécanique analytique* appeared in 1788, before Woodhouse started reviewing, when it received only a very brief mention in the *Monthly Review.* By the time the second edition was published, Woodhouse was no longer a regular reviewer: the reviewer of this edition was probably Peter Barlow, but there is no editor's identification [[Barlow] 1816]. (The review assiduously records additions and alterations, noting that it had been completed after Lagrange's death by Prony and others, and ends with a complete list of Lagrange's papers that had been compiled by Lacroix.)

Space permits only a brief account of Woodhouse's reviews. His style is less magisterial than Playfair's, but with the same tendency to prolixity: he particularly favoured long quotations (a useful device when paid by the page!). Woodhouse was Playfair's junior by twenty-five years; but his reviews

monthly parts, totalling over 500 pages per volume. The April, August and December issues contained appendices devoted to "Foreign Books". All reviews appeared anonymously, but the identities of most reviewers were noted in the editor's copy of the journal (now in Oxford's Bodleian library and available online at British Periodicals Collections II: 1752-1825). At the end of most Woodhouse articles are manuscript abbreviations such as "R. Wood...e" or "R.W." All these attributions are recorded in [Nangle 1955], an indispensable resource. Woodhouse reviewed works on a great range of topics, ranging from metaphysics to foreign travels: in all, between 1798 and 1812, he wrote around 170 articles on works in English, and about 50 on foreign works. Woodhouse was the major reviewer of mathematical works during this period. But other mathematicians who wrote on various topics for the journal were John Leslie (who wrote 31 reviews of English works between 1794 and 1808), James Glenie (who reviewed 49 English works during 1807-1814), and Peter Barlow (who wrote 12 mathematical reviews during 1814-15.) The rate of remuneration for reviewers probably varied; but, according to Nangle, Leslie negotiated four pounds per sheet: this is five shillings per page of an octavo volume.

are as well-informed and his opinions as perceptive as Playfair's. The extent of his reading is formidable; and, unlike Playfair, he did not shirk from incorporating mathematical equations into his reviews. Woodhouse's admiration for Lagrange and Laplace is clear, and he is outspokenly critical of some others.

His 1799 review (No. 2) [39] of Lagrange's *Théorie des fonctions analytiques* has a lengthy historical introduction, describing the method of indivisibles, the Newton-Leibnitz controversy and Newton's concept of fluxions based upon motion. In Woodhouse's view, "Had not Newton been the inventor of this method… very few persons would have contended for its metaphysical or mathematical excellence" (p. 487), but: "That which happened to Aristotle has happened to Newton; his followers have bowed so implicitly to his authority, that they have not exercised their reason" (p. 488). Also, the defence by MacLaurin is so cumbersome that it is plain that he and Newton had "failed to seize the right principle, and the true mode of explanation" (p. 488). Though l'Hospital's *Analyse des infinitement petits* excluded the principle of motion, it is "by no means clear and satisfactory" (p. 490). The analytical concept of "limits of ratios," propounded by d'Alembert, Euler and others is also objected to. In "the Berlin Acts for the year 1772" Lagrange first proposed that "the developement [in series] of functions contained the true principles of the differential calculus, freed from all consideration of infinitely small quantities, or of limits." The work now reviewed "establishes this position more fully" (p. 492). Woodhouse then outlines several pages of Lagrange's analytical exposition, including applications to geometry and mechanics. In conclusion, he urges that: "In questions of real science, national animosity should cease… To be said to rival a De la Place and a De la Grange is no mean praise; men who… have given to France trophies more durable and more glorious than those of any warrior and conqueror" (p. 498).

By the time that he reviewed Lagrange's *Leçons sur le calcul des fonctions* in 1806 (No. 12), Woodhouse had published his own work on the foundations of calculus [Woodhouse 1803], in which he embraced Lagrange's method of series expansions, but with additional provisos on the admissible functions. Here he is more critical, objecting to Lagrange's assertion that expressions such as $(1 + w)^m$ have a series expansion in powers of w

39 Numbers henceforth relate to the entry [[Woodhouse] 1798-1818] in the list of references.

when m is an irrational quantity such as the cube root of 7. [40] More surprisingly, he re-expresses some of Lagrange's results in fluxional notation, being "more intelligible to the generality of English readers" (p. 489). He also points out that formulae for the expansions of cos mx and sin mx as power series in cos x (which Lagrange had not seen in any other work) are in fact given "in a paper written by our countryman Mr. Woodhouse" [Woodhouse 1802]. Though "the matter of [later] chapters is very good," it is likely to be beyond the comprehension of most students (p. 492). He alleges that the work, though "intended as an elementary treatise… originated… in the necessity imposed by the present Government of France… a part… in the plan of universal conquest; and, oddly as it may sound, Geometry and the theory of Analytic Functions are to lend their aid in the subjugation of England" (p. 498). Clearly, Woodhouse's previous wish that "animosity should cease" was overtaken by political events.

The second part of Woodhouse's review examines Lagrange's treatment of functions of several variables, which he again re-expresses in fluxional notation, and notes that a large portion is also in *Théorie des fonctions analytiques*. He then turns to the Calculus of Variations, extensively quoting Lagrange's account of its history and then briefly outlining Lagrange's method. But he again doubts "whether the student will be able fully to comprehend this theory" without consulting other works by Euler, Bossut, La Croix and even "the rough and unpolished solutions of *James Bernoulli*" (p. 510).

Woodhouse's 1799 review (No. 3) of Laplace's *Exposition du système du monde* is less commendatory than might have been expected. Though Laplace aimed at a non-technical exposition, some parts "will only be understood by those who have bestowed a considerable degree of attention on the subject.— The world must look forward with impatience to the appearance of the work which the author has promised on physical astronomy; and in which, what now seems to be obscure will be made evident by mathematical demonstration" (p. 506). A now little-known work by Hassenfratz, reviewed in 1803 (No. 10), is a more simplified exposition of Laplace's *Système du monde* prepared for the students of the École polytechnique.

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40 That it does in fact have such an expansion is obvious from the binomial theorem in its general form: but this was still a contentious issue, as it was believed that no satisfactory algebraic proof had been found for irrational powers. The most satisfactory demonstrations around this time were the little-known one by [Spence 1809], and an even earlier, but more cumbersome, one by [Glenie 1799]: see [Craik 2009], [2013a].

Woodhouse's two-part review (No. 4) of the first two volumes of Laplace's *Traité de mécanique céleste* (Books 1-5) appeared some years before Playfair's (who covered the first ten Books). Unlike the latter, he does not review the history of astronomy in any detail, but instead quotes part of Laplace's introduction. On the foundations of mechanics, he points out the influence of d'Alembert on Laplace's formulation, and he quotes key results using Laplace's differential notation (not fluxions). The excellence and importance of the work are made clear: he ends the first part of his review with the admission that for "the detection of errors and the suggestion of improvements, we have found little opportunity, and felt less inclination. For those who are acquainted with the genius and acquirements of the author of the present work, and who are sensible of the intricacy and abstruseness of its subject we need fear no reprehension..." (p. 478). The second part of the review describes Books 3-5, but in less detail, and gives a useful list of Laplace's earlier memoirs. In answer to the question "if all parts of the universe are subject to the laws of gravitation, what remains to be done? Is not the astronomer's occupation gone?," he ends with a lengthy quotation from Laplace himself outlining topics requiring further study (p. 484-485).

In 1803 and in 1805 (Nos. 9, 11), he reviewed volumes 3 and 4 of the *Traité de mécanique céleste* (Books 6-10). The third volume is devoted to "the perfection of astronomical tables by means of the deductions and results obtained from theory" (p. 492). These comprise calculations of higher-order perturbations to the orbits of all the planets and their satellites, and of the Earth's Moon. On the last, Laplace discusses previous lunar tables, and the recent improved ones by Bürg that employed his theory. The briefer review of volume 4 records that it considers the motion of planetary satellites and comets, and that all that remains to appear was a final eleventh Book on the history of astronomy. (But such was not the case, as sixteen books eventually appeared, and some supplements.)

Later, Woodhouse reviewed three supplements by Laplace, two on capillary action (Nos. 13, 16, 17). In reviewing the second of these, he roundly criticises Laplace for inserting a topic having no place in a work devoted to physical astronomy, and for unsound speculations regarding the nature of intermolecular forces. [41] The remaining supplement, on higher-order perturbations of planetary orbits, and the correction of a previous error, is described as "a short, but by no means unimportant, addendum to the second book".

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41 A full account of Laplace's work on capillarity is [Dhombres 1989].

In 1800 and 1801 (Nos. 5, 6, 7), Woodhouse reviewed La Croix's comprehensive two-volume *Traité du calcul différentiel et du calcul integral*, the supplementary third volume *Traité des différences et des séries...* and his *Élémens d'algèbre*. The contents of these works are summarised, with objections made to Lacroix's sometimes uncritical approach. On the last-mentioned work, for instance, Woodhouse wrote that: "the writer appears to possess greater learning than discernment... He has great merit in having understood, arranged, and reduced to system the labours of other mathematicians" (p. 476).

The first nine pages of Woodhouse's review of the 1250-page *Traité du calcul différentiel et calcul integral* concern only Lacroix's Preface and Introduction on the historical development of calculus. An account follows of Lagrange's algebraic approach, based on series expansions, as given in Chapter 1. The content of each subsequent chapter is briefly described, with occasional criticisms and observations (such as that some results given in Chapter 3 had already been obtained by Waring). Overall, he concludes that: "Although some of the chapters of this work... are by no means secure from criticism, yet,... it may be pronounced to be the most valuable that has hitherto appeared" (p. 491). He then devotes four more pages to recapitulating the history of integral calculus and to a comparison of differential and fluxional notations, stating his preference for the former. The subsequent third volume, devoted to finite differences and series, "is scarcely inferior in point of bulk to the preceding volumes" (p. 498). Though it contains much worthy material, "we wish that M. la Croix had devoted part of the time which he has spent in learning what others had thought and invented, in simplifying those theories which are perplexed and involved" (p. 499).

Woodhouse had a higher regard for Arbogast, whose *Du calcul des derivations* he also reviewed in 1801 (No. 8). He makes a bold attempt to describe Arbogast's unfamiliar (and typographically challenging) notation and his various methods and applications, ending with high praise. First commending Arbogast for his modesty, and for executing his design "simply, clearly, and systematically," he states that "the 'Calculus of Derivations' is an exemplar, a practical proof of what a scientific book ought to be:—it is deep, yet clear; rich without parade; great by little means; and systematic, without the tediousness of formality...".

Woodhouse's 1809 review (No. 15) of the *Tables Astronomiques* of Delambre and Bürg, and volume 3 of Vince's *Complete History of Astronomy* further clarifies a topic considered above. Woodhouse begins by observing that "their matter and its arrangement are nearly the same... because the greatest portion of the English treatise is a transcript of the French: but it is a transcript much more valuable than the original, since it is purged of numerous errors in the tables of Mess. *Delambre* and *Burg*. To typographical correctness the French can advance very weak claims" (p. 449). He mentions the various tables produced since the publication of Newton's *Principia,* Delambre's solar tables and Bürg's lunar tables being based on the most accurate calculations and observations to date. These tables, reproduced in Vince's volume, were "corrected, if we are rightly informed, under the direction of the Astronomer Royal" (p. 453).[42]

Vince also included "tables of the planets and of the motions of Jupiter's satellites, which latter were taken from the third edition of *Lalande's* Astronomy." But Woodhouse regrets that Vince's publication was not delayed, as "perhaps, in a few weeks, we shall receive copies of the French tables of Jupiter and Saturn, and of the other planets," which, barring "typographical errors with which they will probably abound," would be more accurate than Lalande's. He then discusses several theoretical improvements incorporated in the new tables, and observes that Vince has omitted some of Delambre's notes, that would have aided comprehension. Woodhouse then embarks on a lengthy exposition of the theoretical principles on which such tables are constructed, mainly following "Laplace's method". Like Playfair, he objects to Vince's ambiguity concerning the authorship of the tables: in place of phrases such as "our author," the word "Burg" should be substituted.

In a long and appreciative review (No. 15) of the French translation of Gauss's *Disquisitiones arithmeticae* (14), Woodhouse describes many of Gauss's results, observing that some previously described in Legendre's "Theory of Numbers" were obtained independently. He describes Gauss's application to regular polygons inscribed in a circle (noting Ivory's proof in the *Mathematical Repository*); a connection to "Wilson's theorem" described by Waring; and relations to previous work by Euler and Lagrange. Despite such excellence, he finds that Euler writes more clearly than Gauss.

Nearly ten years after his previous foreign mathematical review, Woodhouse reviewed the English translation by Babbage, Herschel and Peacock of Lacroix's *An Elementary Treatise on the Differential and Integral Calculus* [Lacroix 1816] (No. 18). Clearly, he wished to publicise the work of his former students. He commends both the qualifications of the translators and

[42] A footnote (p. 470) ascribes these corrections to "the Rev. Malachi Hitchins, who is lately dead; after having been, for many years, an useful calculator to the Board of Longitude."

the merit of the original work: "if we have not observed the words of the latter precisely followed, we have always found the sense entire; which is by far the most important object." Moreover, Herschel's new replacement of the original Appendix "adds considerably to the interest of the translation" and several notes "usually… have reference to the establishment of first principles" (p. 180-181). The first Note, on the nature of limits and its history, is followed by one on "Lagrange's method of establishing the Differential Calculus, entirely independent of infinitesimals or limits."[43]

But Woodhouse regrets "a tendency to undervalue the Fluxional Analysis": for "we ought not… to compare fluxions, as they were first delivered [by Newton], with the differential calculus as it exists in the present day" that had been transformed since the time of Leibnitz (p. 182). He also objects "to the use of the Italic *d* instead of the Roman d, for denoting a differential, the latter "being less liable to be mistaken for an absolute quantity"; and he complains of the excessive number of errata "though it may accord with the fashion of French authors" (p. 185).

We end this section with just one of Woodhouse's reviews of English works. His very long and detailed two-part review (No. 1) of Hutton's *Mathematical and Philosophical Dictionary* gives full coverage of this ambitious venture:

> A work of this kind has been long a desideratum in the mathematical world… We give full credit to the author, therefore, when he mentions the unfavourable circumstance under which he laboured in having no model before him …
>
> … this Dictionary is likely to become a book of frequent reference and of very general use… we scruple not to pronounce the present Dictionary to be the best work of its kind, and most deserving of the public patronage…
>
> The patience and temper with which he has recorded the various philosophic theories, fanciful and erroneous as some of them undoubtedly are, have excited our admiration and demand our praise.

Woodhouse then embarks on a summary of selected entries under each letter of the alphabet, in which he makes many criticisms. Only a few can be noted here. In general, he believes that: "In explaining the principles of any particular branch of the mathematics, the author is not very perspicuous; as we may exemplify by the article *Acceleration…*" However, the article on *Algebra* is one of the most valuable. He quibbles about "*Centres of Gyration, Percussion, Oscillation &c.…*, where words such as Force, Effort,

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43 The preference of Woodhouse and his former students for Lagrange's algebraic approach to calculus, based on series expansions, and their consequent antipathy to the "doctrine of limits," exemplifies the debate then current regarding the foundations of calculus. See Section 2(*c*).

Impetus, Energy, Rate, &c. are used without sufficient precision." Then, on *Fluxions*, Woodhouse objects that Hutton "has scarcely announced the method of the foreign mathematicians on this subject;– but apparently he sides with his countrymen…"

In the article *Experiment*, Hutton had alluded to

> … the contemptible fall of one of the principal societies… while its members first amuse themselves with magnetical conundrums, spinning electrical wheels, torturing the unseen and unknown phlogistic particles; and finally polluting the source of science, and the streams of wisdom, with the folly of hunting after cockle-shells, caterpillars and butterflies.

Woodhouse, well aware of Hutton's bitter dispute with Joseph Banks at the Royal Society, comments that: "We shall leave the public to determine whether a love of the truth, or resentment of former injuries, induced Dr. H. to write [this] passage."

But Woodhouse ends positively:

> Finally, we strenuously recommend the present volumes to all lovers of mathematical and philosophical pursuits; for, though (as we have observed) they are alloyed by defects, they are also enriched by numerous excellencies, are very abundant in curious and important matter, and possess a decided superiority over every other work of a like nature.

Woodhouse's reviews paint a fascinating picture, showing the reading of, and reaction to, many French works by one of the ablest British scholars of his generation. These not only informed his own later publications, but provided others with detailed information about such analytical works, at a time when war made them hard to come by. Though Woodhouse actively promoted French analysis, he nevertheless advocated a more rigorous attitude towards basic principles and definitions: a matter of necessity if analysis was to achieve intellectual parity with geometry.

7. DISCUSSION

As has been shown, quite a number of British mathematicians and scientists were conversant with recent French work during 1795-1815. But nearly all obtained their knowledge by private study, usually with little input from any formal education and often in isolation. Thus, Spence, West, Toplis, Knight and Herapath pursued mathematics mainly as an unpaid or leisure activity. Ivory managed a spinning mill before joining the Royal Military College and did much of his work after retirement. John Playfair was a Church of Scotland minister for many years, before he obtained the

Edinburgh chair of mathematics (and for which he received only class fees, as the basic salary went to his predecessor, Adam Ferguson, in lieu of a pension). Thomas Young was a medical doctor while pursuing his physical researches and encyclopaedia writing. Even later, John Herschel was an unpaid "gentleman" astronomer and scientific author. Charles Babbage had no regular paid appointment (though he briefly held the Cambridge Lucasian Chair as a sinecure) and sought and received large Government grants to construct his calculating engines. Mary Somerville, abreast of so much in science, had no paid employment and sought none, apart from the income from sales of her books. David Brewster pursued an entrepreneurial career in scientific publishing, before taking up his first regular job as Principal of the United College of St Andrews University. Also, much of the work of observational astronomy remained in the hands of wealthy "Grand Amateurs". Apart from published reviews and disputes in the popular journals, there was little opportunity for communication among this scattered group of individuals, and their sources of remuneration were limited. Until the foundation of more universities and colleges at home and abroad, the employment prospects of aspiring mathematicians and physical scientists remained bleak.

Playfair in Edinburgh and Woodhouse in Cambridge were influential in encouraging others, some directly, and some through their published reviews and essays; and both authors doubtless appreciated the extra earnings that these writings provided. Their reviews, summarised above, speak for themselves in representing their wish for reform and their portrayal of the contrasting states of current scholarship in France and Britain. But there was no concentration of talent that could nurture a British school of analysis, algebra or physical astronomy. Only Ivory, Wallace, Spence, Brinkley, and the younger Herschel and Babbage achieved significant original advances in mathematical research; though the physicists Henry Cavendish, Michael Faraday, Thomas Young, David Brewster and John Leslie made important discoveries in optics, heat, electricity and magnetism in their private laboratories.

In Edinburgh, and elsewhere in Scotland, just a handful of students took advanced (third level) mathematics classes, as these were, in Wallace's words, "required for no profession" [Craik 2000a, sect. 7]. Playfair, and later Leslie, taught calculus and astronomy only in alternate years, and numbers remained small in Wallace's time. At Cambridge, numbers were quite large, but the syllabus, despite Woodhouse's efforts, remained old-fashioned until the mid-1820s. Also, there was little incentive to publish advanced works that few would or could read. The only buoyant publishing sector was that of textbooks for a captive audience of students: mainly on geometry, algebra, astronomy and natural philosophy, these matched the various university and college courses. For instance, In Edinburgh, Leslie supplanted Playfair's geometry textbook with his own inferior one; and later, to Leslie's disgust, Wallace edited a reissue of Playfair's work when he became professor. The multi-volume encyclopaedias enjoyed popularity; a few journals and magazines published fairly short articles; and the *Transactions* of the Royal Societies of London and of Edinburgh, and of the Royal Irish Academy, published longer ones. But authors were liable for major financial losses if they sought to publish their own original works with a commercial publisher. Even those not published at the author's own expense might have to be bought back from the publisher if copies remained unsold after a certain time. [44]

Spence's works, Toplis's translation *A Treatise upon Analytical Mechanics* [Toplis 1814], and George Green's later *Essay on Electricity and Magnetism* [Green 1828] (important but long neglected) were privately published, in Green's case with subsidy from a few subscribers. It is said that, at his death, Toplis still had over two hundred unsold copies of his work [Cannell 2001, 36]. Harte's plan to translate the first ten books of the *Mécanique Céleste* was cancelled after just two books had appeared, doubtless because of financial difficulties. Exceptionally, three of Robert Woodhouse's works were part-funded by the Cambridge University Press. Unlike in France, there was no institutional system outside Cambridge to support the publication of advanced monographs.

Matters improved with the foundation of the benevolent Society for the Diffusion of Useful Knowledge (SDUK) in 1826. This published inexpensive texts on a wide range of educational subjects, aimed at readers whose circumstances did not enable them to access formal instruction. Rivals followed, most notably Dionysius Lardner's multi-volume *Cabinet Cyclopaedia.* Among mathematical authors for SDUK were the Cambridge-educated Augustus De Morgan (differential and integral calculus), Samuel W. Waud (algebraic geometry) and William Hopkins (trigonometry); and its prime mover Henry Brougham wrote physical works. [45] The SDUK survived until

44 More on the main encyclopaedias, Cambridge publications, and the French influence on them is in [Grattan-Guinness 1985].

45 Augustus De Morgan (1806-1871) in 1828 became the first professor of mathematics at the new "London University" (later University College London). Much later, in 1865, he was chosen as first president of the London Mathematical Society [Rice 1997], [1999]. His research concentrated on pure mathematics and on logic [Panteki

1848. Another important influence was the growth of public and subscription libraries in many towns and cities, and the establishment of "Mechanics Institutes" for the education of working men and apprentices.

In Cambridge, a small but growing group of reformers, mostly with Whig sentiments, included Robert Woodhouse, the geologist Adam Sedgwick, and the student members of the short-lived Cambridge Analytical Society. This Society's volume of papers (all by Babbage and Herschel) [Analytical Society 1813], promoting the "continental" calculus against the "dot-age" of Newton's fluxions, had next to no effect and the Society disbanded when its members dispersed after graduation [Enros 1983]. Far more influential was the English translation prepared by Babbage, Herschel and Peacock of Lacroix's *Traité élémentaire du calcul différentiel et du calcul intégral*, with additional notes [Lacroix 1816], and Peacock's book of "Tripos-style" examples [Peacock 1820]. During the 1820s, much-needed reform of the Mathematical Tripos was accomplished by some younger fellows, including George Peacock, Richard Gwatkin and William Whewell, with later support from Duncan Gregory, Robert Murphy and others: see e.g. [Gascoigne 1984], [Becher 1995], [Warwick 2003], [Craik 2007]. Peacock went on to write an influential *Treatise on Algebra* [Peacock 1830]. Whewell, politically a Tory, became Master of Trinity College and an effective reformer of the university; but his later mathematical views were increasingly conservative [Becher 1980a], [Fisch & Schaffer 1991].

By 1830, the intense competition to become a high wrangler, and hence a college fellow, and the equally intense coaching by private tutors such as William Hopkins, ensured that many talented mathematicians learned the new techniques. In due course, some went on to apply these in research, and to become professors in Cambridge and in other universities. Thereby, a critical mass was achieved, and British mathematics flowered again, particularly in applications to physical topics.

Like Spence, the young John Herschel and Charles Babbage (along with John Herapath and a few others in Britain) had investigated the properties and solutions of "functional equations". This and the related "calculus of operators" were early Cambridge mathematical preoccupations, the

2003], and he was one of the group of innovative algebraists that included G. Peacock, D.F. Gregory and George Boole [Durand-Richard 1996]. Though he published nothing on applied mathematics, an early manuscript entitled "Elements of Statics" helped to secure him the London chair. Far from elementary, this shows an awareness of the dynamical ideas of d'Alembert, Lagrange, Laplace and Lacroix. It was written for the SDUK but never published, perhaps because it was thought too advanced [Rice 1997, 271]. I am grateful to Adrian Rice for drawing attention to this manuscript.

first glimmerings of a distinctive research school of pure mathematics.[46] Both these topics stemmed originally from Arbogast, Français and Servois [Grattan-Guinness 1990, 211-219], but the subject had already fallen from favour in France by the time it was adopted in Britain. Such studies, and applications of mathematics to hydrodynamics, optics, astronomy etc., were later encouraged by the establishment in 1840 of the *Cambridge Mathematical Journal*. Its first editor was the short-lived Duncan Gregory (1813-1844), a former Edinburgh student of Wallace and a fellow of Trinity College: see [Crilly 2004a]. Influenced by Peacock's work, Gregory also made advances in abstract algebra, and published a follow-up volume *Examples of the Processes of the Differential and Integral Calculus* [Gregory 1841]. However, Herschel and Babbage took no part in these later advances, largely abandoning pure mathematics for astronomy and mechanical calculating engines respectively when they left Cambridge [Grattan-Guinness 1979]; [1992], [Dubbey 1978].

The picture was less rosy elsewhere. In Scotland, few students could stay on after graduation (if they bothered to graduate), as there were no teaching assistantships except when a professor fell ill, nor any fellowships like those at Cambridge. Also, the importance of the military colleges declined after the departures of Wallace and Ivory from Sandhurst, and of Hutton and Barlow from Woolwich. But mathematical teaching at the University of Ireland improved after 1812, and Trinity College, Dublin seems to have been better than the Scottish universities in providing posts for its top graduates. As a result, research in mathematics and its applications began to flourish in Cambridge and Dublin before doing so in Scotland. Consequently, the preferred solution of many able young Scots was to proceed to Cambridge for further study, after first attending a Scottish university. In due course, several secured academic appointments. For instance, Peter Guthrie Tait (1831-1901), briefly a fellow of Peterhouse, Cambridge, became Professor of Mathematics at the recently founded Queen's College, Belfast and then Professor of Natural Philosophy in Edinburgh. It was Tait in Edinburgh and William Thomson (Lord Kelvin) in Glasgow who eventually led the resurgence of physical research in Scotland.

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46 Useful surveys of British and Irish progress in algebra after 1830 are [Durand-Richard 1996] and [Parshall 2011]. The influence of Laplace's *Théorie analytique des probabilities* on later British algebraists and logicians, especially Peacock, Augustus De Morgan and George Boole, is examined by [Durand-Richard 2012], but their work mostly comes after the period of this study.

Research in mathematics and its applications to physics and astronomy was soon dominated by a network of Cambridge (and some Dublin) graduates, who staffed the ancient universities and the various new colleges founded at home and in the Empire abroad. Among this next generation, the names of Augustus De Morgan, George Biddell Airy, George Gabriel Stokes, William Thomson (Lord Kelvin), William Rowan Hamilton, Arthur Cayley, John Couch Adams, James Joseph Sylvester, Peter Guthrie Tait and James Clerk Maxwell need only be mentioned without further comment.[47]

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APPENDIX

(a) *Other* Edinburgh Review *articles on mathematics and astronomy attributed to John Playfair, with brief comments*

Edin. Rev. **3** (Jan. 1804), 401-410. Agnesi, Maria Gaetana, *Analytical Institutions,* trs. John Colson.

4 (July 1804), 257-272. Horsley, Samuel, *Euclidis Elementorum Libri Priores XII* and *Euclidis Datorum Liber.*

5 (Jan. 1805), 372-392. Mudge, William, *An account of… a Trigonometrical Survey of England and Wales…* [Much on survey methods. A few references to Legendre, and comparison of English and French surveying methods.]

5 (Jan. 1805), 442-451. Small, Robert, *An account of the astronomical discoveries of Kepler: including an historical review…* ["A book of small magnitude, written with precision, and in a style simple and perspicuous."]

8 (July 1806), 451-456. Mendoza Rios's *A Complete Collection of Tables for Navigation and Nautical Astronomy...* ["The two great nautical problems, to the solution of which these tables are peculiarly directed, viz. finding the longitude from lunar observations, and finding the latitude from two altitudes of the sun, and the time between the

[47] See e.g. [Warwick 2003], [Craik 2007], [Flood 2011].

observations, are here resolved by new and simple rules, that do great credit to the ingenuity and invention of the author." (p. 453).]

9 (Oct. 1806), 161-168. L. Mascheroni, *Géometie du compas* (1798 French translation). ["The object of the author is to resolve, by the circle alone, those problems in plane geometry, which are usually resolved by the assistance both of the circle and the straight line." (p. 161).]

9 (Jan. 1807), 373-391. Méchain & Delambre's *Base du Système Métrique Décimal ou Mésure de l'Arc du Méridien entre les paralleles de Dunkerque & Barcelone*, tom. 1. [Playfair regrets that the duodecimal system was not adopted by the French Academicians, rather than the decimal one; but he now favours British adoption of the decimal system, except for division of the circle. He describes the Commission of Borda, Lagrange, Laplace, Monge and Condorcet, reported in *Mem. Acad. 1788*, and later Commissions. Much about survey methods: c.f. his 1805 review of Mudge.]

13 (Oct. 1808), 101-116. Vince's *Observations on the HYPOTHESES which have been assumed to account for... Gravitation from Mechanical Principles.* [This 26-page pamphlet is Samuel Vince's Bakerian Lecture to the Royal Society, that was not accepted for insertion in *Phil. Trans.* Suffice to say that Playfair's critical judgment supports their decision.]

15 (Oct. 1809), 311-333. Account of the steam engine. [Playfair takes issue with part of Olinthus Gregory's *Treatise on Mechanics...* (1807, 2nd edn.), written by Jabez Carter Hornblower: "what is here improperly called a description of the steam engine... is nothing else than a course and illiberal invective against the inventor" (p. 332). He then gives his own outline of James Watt's achievements.]

21 (July 1813), 310-328. Lambton's measurement of the arc of the meridian in India. [Also in [Playfair 1822].]

21 (July 1813), 364-373. *Bija Gannita or the Algebra of the Hindus*, translated by Edward Strachey (London, 1813).

23 (Jan. 1814), 454-475. (attrib. dubious). Cuvier's *Theory of the Earth.* [Some remarks about Biblical chronology and ancient astronomy.]

29 (Nov. 1817), 141-164. *Algebra, with arithmetic and mensuration, from the Sanskrit of BRAHMEGUPTA and BHASCARA*. Translated by H.T. Colebrooke (London, 1817).

30 (Sept. 1818), 407-424. 1818. Kater on the pendulum. [Also in [Playfair 1822].]

(b) ***Some other reviews of foreign works by Robert Woodhouse in the*** **Monthly Review*****, with brief comments***

Mon. Rev. **28** (April 1799), 529-545. '*Mém. Acad. Sci. Paris* for 1790': [Includes papers by Laplace on flux and reflux of the sea; Legendre on particular integrals of differential equations; Coulomb on friction of pivots; several astronomical papers.]

28 (April 1799), 571-579. 'Memoirs of the Academy of Sciences of Lisbon'. [Includes G. Stockler on theory of fluxions.]

28 (April 1799), 582 and **29** (Aug. 1799), 517-524. Girard's 'Resistance of Solids'.

29 (Aug. 1799), 481-490. Prony's 'New Hydraulic Architecture' [Long introductory discourse by W. on "impractical" mathematics and practical applications.]

29 (Aug. 1799), 507-513. D'Alembert's *Oeuvres posthumes.*

29 (Dec. 1799), 506-512. Condillac's *La langue des calculs...*

34 (Apr. 1801), 463-470. L. Carnot's *Réflexions sur la metaphysique du calcul infinitesimal.*

40 (Apr. 1803), 478-482. Montucla & Lalande's *Histoire des mathématiques,* 4 vols. [Despite several defects noted, W. wrote that: "The history of Astronomy is very clearly and satisfactorily given;... for here La Lande is in his element." ... "When we consider the variety and the extent of the subjects treated in these volumes, we cease to wonder at their great bulk: but at the same time, we cannot help wishing that their bulk had been less."]

41 (Aug. 1803), 501-509. L. Carnot's *Géometrie de position.*

48 (Dec. 1805), 449-457. *Mém. de l'Institut de France,* vol. V. [This includes a report by Delambre on Prony's "grand Trigonometric Tables". W. believes, rightly, that "the tables ... could never come into general use [in view of their cost] but could be used for checking other tables and making abridgments."]

48 (Dec. 1805), 470-477. L. Carnot's *Principes fondementaux de l'equilibre et de mouvement.* ["Less abstruse and perplexed than the works of La Place and La Grange, but ... too general in its formulas and principles, and too barren of examples and illustrations"; though much better than his "Geometry of Position."]

52 Apr. 1807), 449-457. *Mémoires presentés à l'Institut.* [Criticism of Ampère.]

56 (Aug. 1808), 456-458. L. Carnot on 'Relations of the distances between five arbitrary points in space' and 'theory of transversals': [W.

doubts whether this work has any useful application in astronomy or physical science.]

56 (Aug. 1808), 458-462. Svanberg et al. 'Operations in Lapland for determining the arc of the meridian.' [W. refers to *Math. Repository* article on angles of spherical triangles.]

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