J Eng Math (2010) 67:95–113
DOI 10.1007/s10665-009-9298-7

Thomas Young on fluid mechanics

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Received: 11 December 2008 / Accepted: 18 May 2009 / Published online: 12 June 2009

Abstract Thomas Young was a prolific scholar who made many contributions to science, medicine and the humanities. Here, his writings on fluid mechanics are reviewed. The best known of these are on tides and on surface tension; but he did much else besides. These include his wide-ranging lectures to the Royal Institution, his rather eccentric reworking of Book 1 of Laplace's *Mécanique céleste*, and papers on pneumatics and hydraulics. Among the latter are perhaps the first observation of transition to turbulence in jets of air; an empirical formula for the resistance of hydraulic flow in pipes, suggested by his own experiments with thin tubes; and probably the first, but incomplete, attempt at a theory of the hydraulic jump or bore. All of this work is characterised by sound physical insight but mathematical limitations.

Keywords Cohesion and surface tension · History of fluid mechanics · Hydraulics · Tides · Water waves

1 Introduction

Thomas Young (1773–1829) is rightly hailed as one of Britain's great polymaths, his achievements recently celebrated in Andrew Robinson's best-selling biography *The Last Man Who Knew Everything* [1]. Young was a child prodigy with an indefatigable appetite for learning foreign languages, both ancient and modern, and for studying and conducting experiments on what was then called "natural philosophy". As a Quaker, he did not attend Anglican-dominated Oxford or Cambridge universities, but instead chose to study medicine in London and Edinburgh, Britain's major centres for that subject. According to his good friend and biographer, Hudson Gurney: "In the autumn of 1794 he went to Edinburgh, and there attended the [medical] lectures of Doctors Black, Munro, and Gregory. He pursued every branch of study in that university with his accustomed intensity, but made the physical sciences more peculiarly the objects of his research" [2, p. 16]. Gurney's work was partly based on an unpublished autobiography by Young. His pursuit of the physical sciences would have brought Young into contact with John

This paper has been written in memory of the late Howell Peregrine. As graduate students in Cambridge, he and I shared a college, an office, and a supervisor (the late T. Brooke Benjamin). Thereafter, we followed somewhat parallel careers at opposite ends of Britain, in Bristol and St Andrews, respectively. I hope he would have approved of this article, which manages to mention, briefly, his beloved Severn bore.

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Playfair, John Robison and Dugald Stewart, Edinburgh's influential professors of mathematics, natural philosophy and moral philosophy. Young's scholarly accomplishments were soon recognised and he was readily accepted socially by the Edinburgh professoriate, Andrew Dalzel, the professor of Greek, becoming a particular friend. After a year in Edinburgh, Young continued his education in Göttingen (where he found the professors less welcoming) and elsewhere on the continent [1, Chap. 3].

To enhance his medical reputation in England, he wished to become a Fellow of the Royal College of Physicians; but they operated an efficient closed shop, restricting their Fellowships to graduates of Oxford and Cambridge. Accordingly, having by then abandoned his strict Quaker views, Young proceeded to Cambridge to take an M.D. degree, though this was then a qualification of low repute. From 1804, he ran a private medical practice at Worthing, near Brighton, and this was augmented in 1811 by his appointment to a London hospital. He published several medical texts, but his medical activities were just one part of his prolific output.

Young is nowadays best remembered for his contributions to the wave theory of light, particularly interference and diffraction; his work on elasticity and bending of beams, commemorated in "Young's modulus"; his explanation of the mechanism of accommodation of the eye and his theory of colour vision; and for his pioneering work on deciphering the demotic and hieroglyphic scripts of ancient Egypt, as represented on the famous Rosetta stone in the British Museum (and later completed by J.-F. Champollion). His extensive writings on mechanical oscillators and on fluid dynamics are less well known, for in these he made few original advances. But, in his own day, these writings helped to inform both the general public and a rising generation of British researchers.

From August 1801 until June 1803, Young held his only academic post, as professor of natural philosophy at the recently founded Royal Institution in London. Thereafter, he devoted himself to his medical practice and to his private researches and prolific writings on a wide range of subjects. He was elected a fellow of the Royal Society of London in 1794, aged just twenty-one and having published a single paper, "Observations on Vision", read to the Royal Society in 1793 by his relative and mentor Richard Brocklesby; see [1, pp. 38–39]. From 1804 to 1829, Young served as Foreign Secretary of the Royal Society, corresponding with several overseas scientists. To the Society, he delivered the prestigious Bakerian lectures in 1801, 1802 and 1804 (on optics and the eye) and the Croonian lecture in 1808 (on the heart and arteries).[1] He finally became a fellow of the Royal College of Physicians in 1809, and in 1827 he was elected a foreign associate of the National Institute of France in recognition of his work on optics. But full appreciation of Young's achievements did not come in his lifetime. Even now, he has been criticised for pursuing interests that were too wide, lacking "the discipline and insight necessary to pursue topics in great depth" [4]. But among his many admirers was Lord Rayleigh, who lectured on Young's scientific writings at a centenary meeting of the Royal Institution in 1899. Though Rayleigh admitted that these were often too concise and obscure, he concluded that "Young occupied a very high place in the estimation of men of science—higher, indeed, now than at the time when he did his work"; see [1, pp. 6–7].

A lengthy biography of Young (Fig. 1) was published in 1855 by Peacock [5], and other biographies are by Gurney [2], Oldham [6], Wood [7], and Robinson [1]. Many but by no means all of Young's papers were republished in the three-volume *Miscellaneous Works of the Late Thomas Young, M.D. F.R.S.,* edited by George Peacock and John Leitch [8]. In this article, quotations are usually identified by referring to this collection, rather than to the sometimes hard-to-find originals. Similarly, quotations from his lectures given at the Royal Institution [9], first published in 1807, are identified by pages in the 1845 second edition [10] edited by Philip Kelland.

2 Young's lectures

2.1 Overview

During each of his two years at the Royal Institution, for a salary of £300 a year, Young gave three courses of lectures and helped with other administrative duties. He gave fifty lectures during the 1802 session, and probably

[1] For more on Young's activities at the Royal Society see [3].

Fig. 1 Engraved portrait of Thomas Young, from an oil painting by Sir Thomas Lawrence; reproduced from frontispiece of Peacock [5]

sixty in the following year. For these, he published a lengthy *Syllabus* indicating the scope of his intended courses [11]. (The St Andrews University Library copy of the *Syllabus*, previously owned by the physicist James D. Forbes, carries the flyleaf inscription: "This work contains the first publication of the Principle of the Interference of Light. Art. 376".) The Institution's lectures were open to women as well as men, and they attracted a fashionable clientèle. In Young's own view, "the Royal Institution may in some degree supply the place of a subordinate university, to those whose sex or situation in life has denied them the advantage of an academical education in the national seminaries of learning" [10, p. 2]. However, it seems that his lectures were not popular, since the audience's expectations "tended more to entertainment than to expositions filled with Young's professed "elegance" and "reason"" [1, p. 92]. Young himself later admitted that his style had been "more adapted for the study of a man of science than for the amusement of a lady of fashion" (from Young's autobiographical sketch, quoted in [1, p. 86]).

Young's early resignation was in part the result of his unpopularity as a lecturer, which contrasted with the acclaim of Humphry Davy's lectures on chemistry. But it also reflected his disenchantment with the administration of the Royal Institution, which, following the departure of its founder Count Rumford, sought to attract the fashionable aristocracy at the expense of the "lower classes" eager to receive an education. Nevertheless, Young prepared the texts of sixty lectures for publication, and these appeared in 1807 as *A Course of Lectures on Natural Philosophy and the Mechanical Arts* [9]. Young never received the promised (and then large) sum of £1000 for these Lectures, "in consequence of the bankruptcy of the publisher" [4, p. 189]. A later edition [10] was edited by Philip Kelland, and a facsimile of the original edition, with an introduction by Nicholas J. Wade, appeared in 2002. An excellent survey of Young's lectures, and of the early history of the Royal Institution, is given by Geoffrey

Cantor [12], who has carefully examined Young's twenty surviving manuscript notebooks preserved in University College, London.

Young's *Lectures* are remarkably wide-ranging and informative, displaying his wide knowledge and keen physical insight. But Young's biographer, George Peacock (an eminent Cambridge mathematician and Dean of Ely cathedral), was damning: "If, indeed, these lectures were delivered nearly in the form in which they were printed, they must have been generally unintelligible even to well-prepared students" [5, p. 136]. Certainly, for a modern mathematically trained reader they are immensely frustrating: no doubt in deference to his audience at the Royal Institution, but also in line with his own inclinations, Young used no mathematical or symbolical notation whatsoever, preferring instead to describe everything in words only. As a result, he had to resort to cumbersome physical descriptions of relationships between quantities that can be readily and more clearly expressed by simple algebra. One suspects that his audience would have made no more of his circumlocutions than they would if he had used mathematics.

In fact, Young had intended to lecture also on mathematical topics. In his *Syllabus* [11], he proposed not only the three parts on Mechanics, Hydrodynamics and Physics that he delivered, but also a (separately paginated) thirty-two-page fourth part on "Mathematical Elements" that was never given. The lectures of the first three parts comprise the first volume of [9]; the second volume begins with his articles on mathematics, and these are followed by an extensive bibliography that is a testament to Young's wide reading, reprints (some revised) of several of his earlier papers, and an index. In his later edition of Young's *Lectures* [10], Philip Kelland silently omits the mathematical articles and the reprints, and incorporates an updated bibliography into the first volume.

George Peacock assessed the mathematical writings as follows:

> The mathematical Elements of Natural Philosophy … were partly reprinted from the Syllabus of his lectures, which appeared in 1802. They would appear to have been regarded with no small degree of favour by their author … but any student who followed Dr. Young's advice [on how to read them]… would most probably have risen from his labour without retaining a single definite conception either of the propositions or their proofs [5, pp. 190–192].

Part 1 of the *Lectures* is devoted to twenty lectures on mechanics. This begins with nine lectures on the standard topics of equilibrium and motion of masses under applied forces, collisions, levers and pulleys. These are followed by the less-expected topics "Drawing, Writing, and Measuring", "Modelling, Perspective, Engraving, and Printing", and "Passive Strength and Friction", the last including flexure and stiffness of beams where "Young's modulus" was first introduced. More "Mechanical Arts" follow in the remaining lectures, giving a comprehensive overview of such matters as architecture, carpentry, flexible fibres, timekeepers, raising of weights by cranes and other machines, and "Changing the Forms of Bodies" by mills, presses, lathes, glassblowing and so forth. The concluding lecture sketches the entire history of mechanics.

Part 2, entitled "Hydrodynamics", consists of another twenty lectures. The first ten encompass hydrostatics, hydraulics, fluid friction in rivers and pipes, hydraulic pressure, hydraulic and pneumatic instruments and machines, and the history of hydraulics and pneumatics. These are followed by four lectures on sound, harmonics and musical instruments. The final six lectures are on optics and optical instruments, vision, light and colours, and the history of optics. Though it nowadays seems odd to find optics included under the title "Hydrodynamics", it should be remembered that Young regarded light as due to vibrations of an imponderable fluid aether, and so broadly equivalent to sound in air. Young's early support for the wave theory of light brought him into conflict with those of the British scientific establishment who adhered to Newton's corpuscular theory; and his vindication won him a high place in the history of optics.

Part 3, "Physics", begins with eight lectures on astronomy and gravitation, finishing with "The Tides" and the history of astronomy. These are followed by twelve lectures on the properties of matter (including cohesion and capillarity), heat, electricity, magnetism, meteorology, natural history and the "history of terrestrial physics".

To give the flavour, a few portions of his account of mechanics and hydrodynamics are here presented. The subject of cohesion and capillarity is discussed in a later section.

2.2 Motion of pendulums

In lecture V, Young describes the isochronous oscillations of a cycloidal pendulum and relates this to small oscillations of a simple pendulum. However, to avoid using formulae, he has to resort to physical language that now seems contorted. Thus, citing Huygens' *Horologium oscillatorum* of 1673, he writes that "The absolute time of the descent or ascent of a pendulum, in a cycloid, is to the time in which any heavy body would fall through one half of the length of the thread, as half the circumference of a circle is to its diameter. It is, therefore, nearly equal to the time required for the descent of a body through 5/4 of the length of the thread" [10, p. 35]. In present-day notation, this result is just the familiar

$$\frac{\tau}{4} = \frac{\pi}{2}\left(\frac{l}{g}\right)^{1/2}$$

where τ is the period of one complete oscillation, g is the acceleration due to gravity, and l is the length of the thread. (His later approximation is equivalent to taking $\pi^2 = 10$.)

2.3 Discharge from a pipe

In lecture XXIII, Young gives a lengthy and rather turgid account of hydraulic flow in pipes and siphons. Citing Daniel Bernoulli's *Hydrodynamica* of 1738 and after some physical discussion, Young states that the velocity of efflux from a pipe under gravity, when connected to a reservoir, is the same as "the velocity of a body falling from the whole height of the surface of the reservoir" above the pipe's orifice [10, p. 211]. This is just "Torricelli's Law", $u = (2gh)^{1/2}$ where u is the velocity, h the height and g acceleration due to gravity, but Young neither says so nor states this formula. However, he does go on to say that this is often an unsatisfactory approximation, due to contraction of the stream at the efflux (a fact already known to Isaac Newton).

Instead of giving the above simple formula, Young writes that:

> The velocity may be found … by multiplying the square root of the height of the reservoir, expressed in feet, by 8, or more correctly, by $8\frac{1}{44}$; thus, if the height be 4 feet, the velocity will be 16 feet in a second; if the height be 9 feet, the velocity will be 24 …, if the height were 14 feet, the velocity would be 30 feet in a second, and a circular orifice an inch in diameter would discharge exactly an ale gallon in a second [10, p. 211].

His factor of 8 corresponds to taking $g = 32$ feet/s^2. Original units are retained in this paper: for future reference, a British imperial foot is 30.48 cm., a British inch is 2.540 cm, a French inch or pouce is 2.707 cm. He notes that this result "appears at first sight extremely paradoxical" since the water discharged from a vertical pipe 16 feet long acquires a velocity of 32 feet per second. Therefore, each particle of fluid traversing the full length of the pipe experiences gravity for just half a second; but in common circumstances the action of gravity would require a *whole* second in order to produce this velocity. He tries to explain this supposed paradox by asserting that, near the entrance to the tube, "it may be shown that the portion of the accelerating force … is twice as great as the pressure of the fluid on a part of the vessel equal in extent to the orifice" [10, pp. 215–216]. But his argument is unclear.

The next lecture XXIV, "On the friction of fluids", concerns the additional frictional drag forces that operate in pipes and rivers. He begins by praising the work of Pierre Du Buat [13] from 1786, before which "it was almost impossible to apply any part of our theoretical knowledge of hydraulics to practical purposes" [10, p. 222]. Discussion of more of Young's work on hydraulics and pneumatics is deferred to a later section.

2.4 Surface waves

In the same Lecture XXIII, Young rightly observes that:

> it does not appear that the laws of the vibrations of fluids in pipes will at all serve to elucidate the phenomena of waves. Sir Isaac Newton has supposed that each wave may be compared with the fluid oscillating in a

> bent pipe; but the analogy is by far too distant… The motions of waves have been investigated in a new and improved manner by Mr. Lagrange [in his *Méchanique analitique*].

He then claims to "have given a concise demonstration of a theorem similar to his [Lagrange's], but perhaps still more general and explicit." He asserts that these demonstrations, subject to appropriate conditions of incompressibility and absence of friction, show that "any small impulse communicated to a fluid, would be transmitted every way along its surface with a velocity equal to that which a heavy body would acquire in falling through half the depth of the fluid" [10, p. 213].

This velocity, of course, is just Lagrange's $c = (gh)^{1/2}$ where h is the depth: less by a factor of $2^{-1/2}$ than the velocity given by Torricelli's Law of efflux. This is the correct result for all periodic waves of small amplitude in water that is shallow compared with the wavelength, but Young rightly remarks that it overestimates the true velocity of waves with lengths short compared to the depth. Young also remarks that, from his observations, "where the elevation or depression of the surface is considerably extensive in proportion to the depth, the velocity… [is] frequently deficient one eighth or one tenth only of the whole". This comment about the propagation velocity of *nonlinear* waves in shallow water is one of the earliest known. Unfortunately, it is not generally true: for example, as found by Scott Russell in 1844 and much later confirmed theoretically, solitary waves of elevation travel with a velocity greater, rather than less, than c (and weakly nonlinear periodic gravity waves in deep water also propagate with a velocity slightly greater than that of infinitesimal waves).[2] But Young's observations of waves in a small tank were probably influenced by surface tension. (It is now known that this plays a dual role: the velocity of linear waves is increased, but waves of finite amplitude usually have velocities less than this linear value: see e.g. Craik [19, pp. 178–179].)

Young then gives a correct account, entirely in words, of the propagation of an initially stationary disturbance along a narrow canal: "the original elevations and depressions, extending their influence in both directions, will produce effects only half as great on each side, and these effects will then be continued until they are destroyed by resistances of various kinds." And he considers the effect of "two equal and similar series of waves" propagating in opposite directions, noting that this is identical to that of reflection at a steep wall or bank. Similarly, waves "on a broad surface" usually constitute a number of concentric circles, and reflection at a barrier is such that the reflected waves "appear to diverge … from a centre beyond the surface … and to be subject to all those laws, which are more commonly noticed in the phenomena of reflected light" [10, pp. 218–219]: see Fig. 2 (No. 264). Here, he shows a clear physical understanding of what was later exploited mathematically as the "method of images".

He then describes his apparatus consisting of a shallow glass-bottomed vessel with sloping sides that "avoid the confusion … from continued reflections". Waves excited by a rod or wire "may be easily observed, by placing a light under the vessel, so that their shadows may fall on a white surface, extending in an inclined position above" [10, pp. 219–220]: see Fig. 2 (No. 265). He is known to have demonstrated this in his lectures during 1802–1803, and he certainly used it to clarify his ideas about the propagation of light waves. (Does anyone know of an earlier account of such an apparatus?) It is also known that the same apparatus was later used by Michael Faraday in his Royal Institution lectures; see [7, p. 138]. Young used his apparatus to demonstrate diffraction when waves pass through a narrow aperture, and their interference when wavetrains meet. The former demonstration (Fig. 2, No. 266) is the hydrodynamic equivalent of Young's famous slit experiment in optics. The latter demonstration with intersecting circular wavetrains reveals hyperbolic curves where the water remains smooth, with strongly agitated motion in between (Fig. 2, No. 267).

Summing up, Young considered that:

> The subject of waves is of less immediate importance for any practical application than some other parts of hydraulics; but besides that it is intimately connected with the phenomena of the tides, it affords an elegant employment for speculative investigation, and furnishes us with a sensible and undeniable evidence of the truth of some facts, which are capable of being applied to the explanation of some of the most interesting phenomena of acustics [*sic*] and optics.

[2] On the relevant theory, see for example papers by Peregrine [14,15], Drazin and Johnson [16] and Craik [17,18].

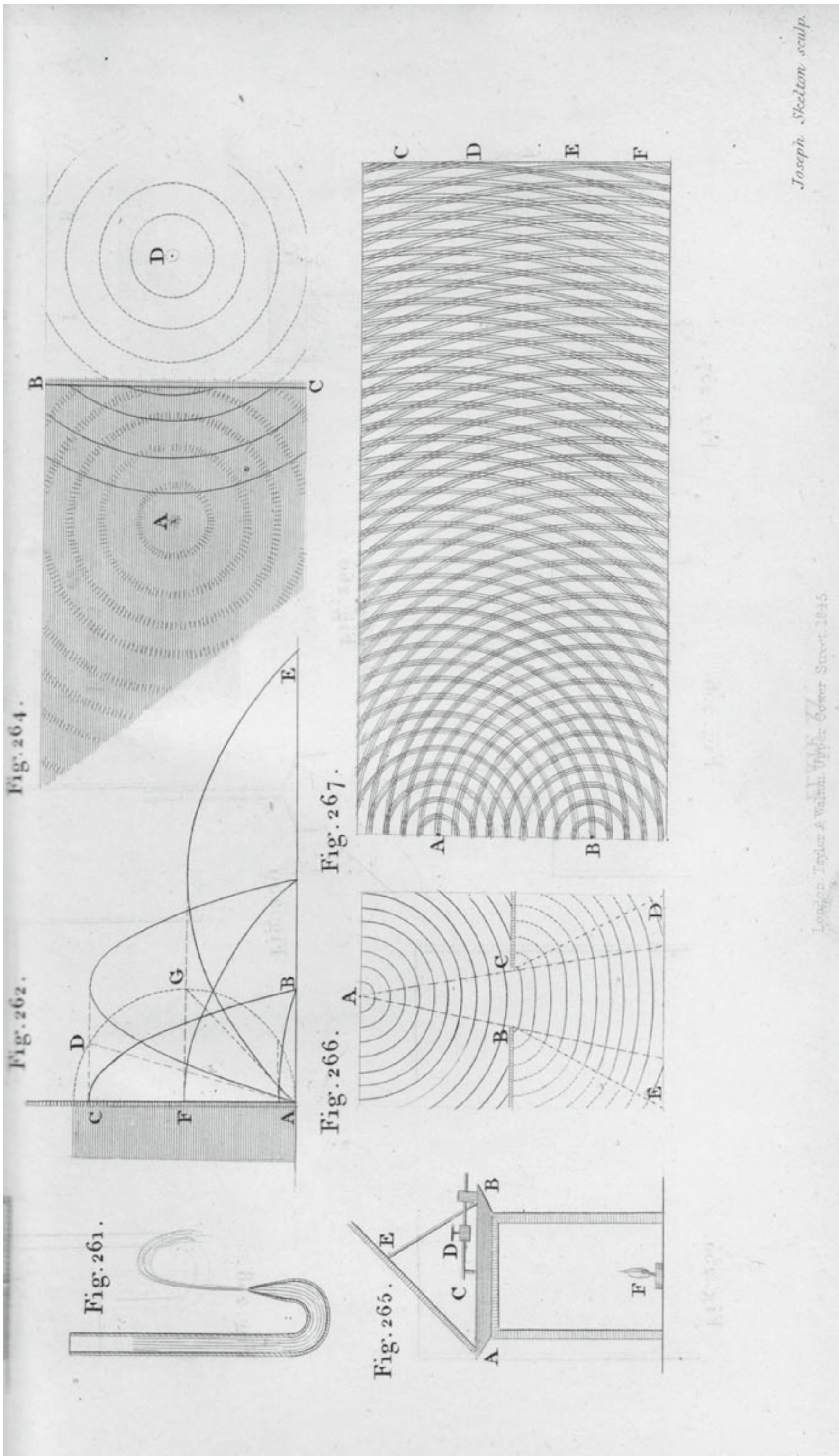

Fig. 2 Part of Plate XX from Young [10]. Figure 264: Reflection of circular waves at a plane wall. Figure 265: Water wave apparatus. Figure 266: Wave diffraction at a slit. Figure 267: Interference of circular wave trains

He then concludes the lecture by drawing attention to the analogy between surface waves and the motion of liquid in elastic pipes and tubes. In blood vessels, "the pulse moves on with great rapidity" due to elasticity of the vessels and the temporary action of the "muscular coats of the arteries; … while the whole mass of the arterial blood continues … to advance with a much smaller velocity; like the slow stream of a river, on the surface of which undulations are continually propelled …" [10, p. 220]. In his 1808 Croonian lecture to the Royal Society, Young emphasised that "the muscular powers of the arteries have very little effect in propelling the blood" (quoted in [7, pp. 91–92]).

3 Young's account of Laplace's *Mécanique céleste*

In 1821, Thomas Young published, anonymously, his *Elementary Illustrations of the Celestial Mechanics of Laplace. Part the first, comprehending the first book* [20]. Laplace's *Mécanique céleste* [21] appeared intermittently in five volumes during 1799–1825 and had a profound effect on applied mathematics. Employing mathematical analysis based on partial differential equations, Laplace went far beyond Newton's *Principia* in revealing the "mechanism of the heavens". Topics studied by him include planetary motion with perturbations and secular inequalities; the gravitational attraction of ellipsoids and the form of self-gravitating and rotating homogeneous bodies; ocean tides and atmospheric oscillations; precession and nutation of the Earth, libration of the Moon, and the motion of Saturn's rings; the theory of motion of each of the planets and their satellites; atmospheric refraction; and capillary attraction.

In 1805 and 1808, respectively, John Toplis and John Playfair publicly bemoaned the inferiority of British mathematicians, rightly asserting that few had mastered the new analysis to the extent of being able to read the works of Laplace, or even those of earlier writers such as Euler and d'Alembert; see e.g. [22]. Even earlier, in a 1798 letter to his friend Andrew Dalzel, Young himself wrote that: "I am ashamed to find how much the foreign mathematicians for these fifty years have surpassed the English in the higher branches of the sciences. Euler, Bernouilli [*sic*] and d'Alembert have given solutions to problems which have scarcely occurred to us in this country" (quoted in [7, p. 65]). One of the few British mathematicians to engage successfully with contemporary continental mathematics was James Ivory, who had studied first at St Andrews and then with Playfair in Edinburgh. Ivory's work on the gravitational attraction of ellipsoidal solid bodies, and his calculation of the "figure of the Earth" due to self-gravitation and rotation, were hailed for improving on some aspects of Laplace's treatment; see [23,24].

John Toplis, educated at Cambridge but by then headmaster of a school in Nottingham, tried to popularise the works of Laplace by preparing an English translation, with explanatory notes, of the first book of the *Mécanique céleste* [25]. A separate translation of the same first book, by Henry Harte of Dublin, appeared some years later [26], just after Young's *Elementary Illustrations*. Though Toplis and Young deal only with Laplace's introductory "first book" (and Harte later translated the second book), the complete work ran to fifteen "books" published in five volumes. A full English translation, with copious explanatory notes, of the first four volumes of Laplace's *Mécanique céleste* was eventually given by the American, Nathaniel Bowditch [27]. Modern scholarly assessments of Laplace's achievements are given by Grattan-Guinness [28] and Gillispie [29].

Laplace's "first book" describes the laws of mechanics, the motion of point masses, the equilibrium of systems of masses and of fluids, the motion of bodies composed of connected point masses, the motion of solid bodies, and the movement of fluids. All this is necessary preparation for his subsequent celestial applications and also serves as an introductory text on mechanics of solids and fluids, written in modern analytical notation. It was doubtless this latter aspect that attracted Toplis, Harte and Young. But Young's *Elementary Illustrations* is far from being a straight translation and commentary. Rather, he undertakes some major reworking of the material that strikes the modern reader as decidedly odd.

Young's own mathematical skills were of a traditional sort: he was adept in Euclidean geometry and fairly proficient in algebra and in calculus. When combined with his sound physical intuition, he was able to deploy this limited mathematical range to good effect in his researches. But his choosing to publish a work on Laplace's highly analytical treatise now seems surprising. Perhaps he viewed it as a challenge to his considerable intellect to confront this major scientific work. He wrote indefatigably and doubtless found that writing was a good way of learning. Some clues are to be found in Young's Preface.

Regarding his translation, he "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." Finding some parts of the "elementary doctrines of motion" and some other subjects to be "more natural and satisfactory" when expressed in more familiar form, Young "felt himself compelled to substitute for Mr. Laplace's introductory investigations" some of his own former publications on mechanics. Approximately the first one hundred pages are filled in this way, incorporating a revised version of the Mathematical Elements from his *Syllabus* and *Lectures*. Elsewhere, Young adds many passages (indicated by square brackets) to his translation. He also inserts many diagrams although Laplace, on ideological grounds, ensured that his work contained none. As a final liberty, in his chapter VIII entitled "Of the Motion of Fluids", he replaces the first part of Laplace's text by a lengthy seven-page quotation from S.D. Poisson's *Traité de Mécanique* [30], "which is nearly similar, but reduced to more elementary principles, and in some instances more clearly expressed" [20, p. 279]. This section derives Euler's equations for nonviscous flow "by the principle of Dalembert", and without mentioning Euler's name (a usual omission in French works of this time).

Towards the end of his Book I, Laplace derives the equations governing small oscillations of a fluid extending in a thin layer over an entire rotating "spheroid" (the Earth's surface) and subject to external forces due to the gravitational attraction of external bodies (the Moon and Sun). These are the now-famous *Laplace tidal equations* applied to oceans and atmospheres of unlimited extent. It is noteworthy that they incorporate terms deriving from the "Coriolis force".[3] But these equations were "left hanging" in Book I, and Laplace did not return to them until Book IV, where he derived their solutions. For a good account of Laplace's theory of tides, and its reception, see [31].

Young chose to continue the story in his own way. Complaining that Laplace's "refined investigation" was "unnecessarily general", he confines attention to water waves in a narrow canal [20, p. 318]. By rather dubious arguments, he shows that the waves' surface profile must advance with horizontal velocity $\sqrt{gy}$ where y is the water depth (see above). This result, true for long waves of small amplitude in shallow water, was known to Young from Lagrange's *Méchanique analitique* [32] and from his earlier paper [33]. In a "Scholium" [20, p. 322], Young remarks that: "each particle of the surface will describe an oval figure, which it will be simplest to suppose an ellipsis; the motion in the upper part being direct … and in the lower part retrograde." He does not seem to have had only sinusoidal waves in mind; nevertheless, this is one of the first published statements that particle paths may be ellipses. The first derivation that the particle paths of sinusoidal waves are ellipses in water of arbitrary depth is usually credited to Airy's *Tides and Waves* of 1841 [34], though it easily follows from results given in 1776 by Laplace; see [17, p. 12]. Young further argues that diverging circular waves must propagate outwards with this same speed, while their amplitude decreases as the [inverse] square-root of distance from the centre. Then he goes on to discuss the interference of [linear] superpositions of waves and to explore an analogy with waves in elastic "chords" [20, pp. 322–327]. In an earlier comment [20, pp. 306–307], Young had alluded to the elasticity of water as the means of transmitting to great depths any changes of pressure at the surface, rightly disputing on physical grounds the instantaneous transmission required with an incompressible fluid model.

Young's *Elementary Illustrations* ends with two Appendices, one on "The Cohesion of Fluids" and the other on "Interpolation and Extermination". The former is discussed below in the section on surface tension. He describes the latter as an "application of Taylor's theorem, which may be found of considerable utility in computing the forms of the surfaces of fluids …" (Preface to [20, p. *iv*]). This is just a brief account of the theory of finite differences, expounded many times before.

The *Elementary Illustrations* is a curious work, described by Young as a "Mosaic", incorporating much of his own work and some of Poisson's, and far from true to the spirit of Laplace's original. The many diagrams, the geometrical treatment of mechanics, and the organization of the whole into "Theorems", "Corollaries", "Lemmas" and "Scholia" are alien to Laplace's text and look back to an earlier age. Young's many insightful remarks derive from sound physical intuition rather than sophisticated mathematical analysis.

[3] Gaspard Coriolis, born in 1792, was just seven years old when Laplace's first volume appeared.

4 Young on pneumatics and hydraulics

While at Cambridge, Young investigated the similarities between sound and light. This work is described in an early paper read to the Royal Society in 1800 [35].[4] It begins with two sections seemingly little-connected with either sound or light: "Of the quantity of air discharged though an aperture" and "Of the direction and velocity of a stream of air". The former concerns air escaping from a small hole or tube inserted in a bladder that is maintained under constant pressure; Young determined that the quantity of air discharged in a given time is proportional to the "subduplicate ratio of the pressure" (i.e., its square root). The second section describes the lateral spreading of a jet of air with distance from its source. He measures this by directing the jet normally onto a thin layer of liquid on a plate and observing the radius within which the liquid is displaced. Though this nowadays may seem a rather crude approach, it yielded an important observation:

> One circumstance was observed … which it is extremely difficult to explain, and which yet leads to very important consequences: … When the velocity is as small as possible, the stream proceeds for many inches without any observable dilatation; it then immediately diverges at a considerable angle into a cone, … and, at the point of divergency, there is an audible and even visible vibration… When the pressure is increased, the apex of the cone approaches nearer to the orifice of the tube [8, Vol. 1, pp. 68–69].

This phenomenon is sketched in [8, Fig. 84], where there is a clear representation of small eddies in the cone-like region; and Young noted a connection with the jet above the flame of a candle. This is perhaps the first clear description of transition to turbulence, though Young does not use this expression; and it is noteworthy that Young appreciated its "very important consequences". Later observations and theoretical studies of this phenomenon by Le Conte in 1858, Tyndall in 1867, and Rayleigh in 1879 are noted in [36, pp. 208–209].

In 1808, Young published an article entitled "Hydraulic Investigations, subservient to an intended Croonian Lecture on the Motion of the Blood" in the *Philosophical Transactions of the Royal Society of London* [37]. There, he proposed a total resistance law for flow through a uniform pipe or tube, based on the already much-used formula

$$f = a\frac{l}{d}v^2 + 2c\frac{l}{d}v,$$

where f is "the height employed in overcoming the friction", v the velocity of fluid, l is the length and d the diameter of the pipe, and a and c are functions of d to be determined empirically from measurements. In support of this, he cites his own experiments as well as those previously published by Du Buat, Couplet, Bossut, and Gerstner. He also suggests a somewhat similar formula for rivers, with the cross-sectional area of the pipe replaced by that of the river. Resistance laws with terms proportional to both v and v^2 were originally proposed in Newton's *Principia* (Book II, Sect. 3) for projectiles moving in air. This form was adopted for pipe and channel flows in 1786 by Du Buat [13]. For later applications by Coulomb in 1800 and Prony in 1804 see, for example, [38, Chap. X].

A closer examination reveals something of Young's methods. His own experiments are cursory, only three in number, for very narrow tubes with diameters of 1/42 and 1/183 pouces or French inches, a unit chosen to conform with Du Buat's. (These diameters are respectively 0.645 and 0.148 mm approximately.) In contrast, Pierre Du Buat's two-volume work *Principes d'hydraulique*… [13] described a great many experiments, mostly new but also the earlier ones of Couplet, Bossut and Gerstner. Almost all of the data repeated by Young in the table on pages 168–169 of his article are drawn from the corresponding tables on pages 72–76 of [13]. But Young has chosen only a small sample of the latter data, sensibly rounding up the measurements to fewer significant figures, but less sensibly ignoring Du Buat's distinction between vertical, inclined and horizontal tubes.

Du Buat had proposed his own empirical formulae that we need not discuss here, other than to say that they involved logarithms; see [38, p. 131]. These agreed reasonably well with all his experimental data, but for Young's very narrow tubes the formulae fail. Young proposed his own formulae that gave results in satisfactory agreement both with Du Buat's data and with his very narrow tubes. His functions $a(d)$ and $c(d)$ are given by

[4] I am grateful to Olivier Darrigol for drawing my attention to this paper, which I had initially overlooked.

$$a = 10^{-7}\left(430 + \frac{75}{d} - \frac{1440}{d+12} - \frac{180}{d+\frac{1}{3}}\right),$$

$$c = 10^{-7}\left(\frac{900\,d^2}{d^2+1000} + \frac{1}{\sqrt{d}}\left(1050 + \frac{12}{d} + \frac{0.9}{d^2}\right)\right),$$

in the appropriate French units (1 pouce or Paris inch is nearly 2.7 cm). Later, he states the equivalent formulae in "English inches". Young gives no indication of how he derived the numerical values in these rather strange formulae: one can only suppose that he employed trial and error.

In order to compute the fluid velocity v connected with a given case, he adds to f "the height required for producing the velocity, independently of friction". He takes this to be $v^2/550$ in preference to Du Buat's $v^2/478$: both are modifications of Torricelli's Law, $h = v^2/2g$, for g is about 360 pouce/s^2. The whole height of fall h of the fluid is therefore equal to $f + v^2/550$, and so

$$h = \left(\frac{al}{d} + \frac{1}{550}\right)v^2 + \frac{2cl}{d}v.$$

The positive root of this quadratic equation gives the velocity v corresponding to the fall h for a given pipe, and this is what is compared with the velocities found in the various experiments for which d, l and h were known.

Though this is not pretty mathematics, it is effective in the sense that it gave good agreement with the experimental data. Young conducted his own few experiments with thin tubes because of his interest in blood flow; then, on finding that Du Buat's empirical formulae were inapplicable to such thin tubes, he proceeded to devise his own. However, this work seems to have had little later influence. French hydraulics of the period is well described by Darrigol [36], but he does not mention Young's work in this connection.

In fact, for very thin tubes, Young's empirical formula does *not* reduce to the known exact result for laminar Poiseuille flow in a pipe, as it should. Using the exact laminar formula for the volume flux (as given for instance in [39, p. 180], the expected mean velocity v was calculated for the conditions of Young's three experiments. Considerable differences are found, though the flows in these thin tubes must have been laminar. In the same units, the laminar formula yields $v = 17.88$ for the tube with diameter 1/42 pouces; but Young measured v as 14.4. And the laminar formula gives $v = 2.168$ and 1.225 for the tubes with diameter 1/183 pouces; while Young measured the much smaller $v = 0.53$ and 0.27. It seems likely that Young overestimated the diameters of his tubes, or that they contained unnoticed constrictions: this suggestion would be consistent with the roughly constant *ratios* of velocities in the two experiments with the thinnest tube.

In the same article, Young discusses the added resistance due to "flexure" in pipes and rivers, and he mentions flow through elastic tubes, including blood flow. He then turns to waves in channels, noting that they, like sound, grow in amplitude when propagating along convergent channels.

The final section of this paper [37, pp. 181–186] concerns "the Effect of a Constriction advancing through a Canal", and is perhaps the first attempt at a theory of the hydraulic jump or bore. Young envisages a vertical barrier advancing with velocity v into a canal containing liquid that is initially at rest with depth a (Fig. 3). He supposes that there is a region adjacent to the moving barrier where the liquid depth is raised to x, and that a "wave" propagates away from the barrier with a velocity y, within which the depth changes from x to a. He more or less correctly deduces the continuity condition that

$$a - x = \frac{-av}{y - v},$$

though he introduces an extraneous $\mp$ before v in the denominator (presumably to allow for a receding as well as an advancing barrier) and the minus sign was erroneously omitted from the numerator. He then embarks on an obscure calculation, supposing that the wave has the shape of a ramp with constant angle of 45 degrees, and he thereby arrives at a formula for the wave-speed y. From this, he concludes that "y must be somewhat greater than the velocity of a wave moving on the surface of the elevated fluid". This is unconvincing, but Young has unerringly identified an interesting physical problem that he lacked the expertise to solve. It was over 20 years later that Jean-Baptiste Bélanger made further advances towards a satisfactory theory, following earlier observations

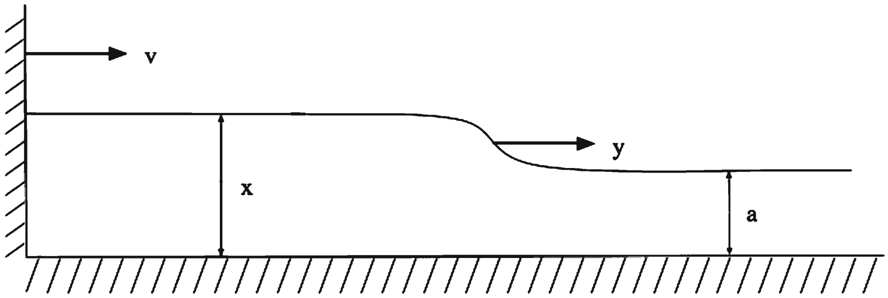

Fig. 3 Definition sketch for Young's hydraulic jump model

and unsuccessful theoretical attempts by Giorgio Bidone around 1820: see [36, pp. 224–225], [38, pp. 143–144], [40]. Howell Peregrine has left his own mark on this topic both through his papers, such as [41], and his excellent photographs; see e.g. [42, p. 116].

5 Young on tides

In 1823, Young wrote a long article on "Tides" for the six-volume *Supplement* to the *Encyclopaedia Britannica*, edited by Macvey Napier [43]. In fact, for this Supplement, he wrote no fewer than 63 articles, large and small and on a wide range of topics; see [1, Chap. 12]. Many appeared anonymously as Young was anxious not to be thought neglectful of his medical practice. But he later allowed his authorship to be identified: his article on "Tides" appeared under the initials "A.L.", but he is identified elsewhere in the volume as the author of this and other articles.

Ten years previously, he had published "A Theory of Tides" in *Nicholson's Journal* [44]. Much of this explored an analogy with the motion of a pendulum subject to periodic forcing. In his own words:

> The oscillations of the sea and of lakes, constituting the tides, are subject to laws exactly similar to those of pendulums capable of performing vibrations in the same time, and suspended from points which are subjected to compound regular vibrations of which the constituent periods are completed in half a lunar and half a solar day [8, Vol. 2, p. 280].

He also remarked on the nonlinear steepening of waves and tidal bores, observing that:

> The slight difference of the ascent and descent of the tide remarked by Laplace in the observations at Brest [in Book IV of *Mécanique céleste*] may be explained by comparison with the form of a common wave, which, where the water is shallow, is always steeper before. This circumstance arises from the greater velocity with which the upper parts of the wave advance, where the differences of the depths become considerable … and it is, perhaps, somewhat increased by the resistance of the bottom. Where the tide travels far in shallow channels, its irregularity of inclination increases more and more: for instance, in the Severn, it assumes the appearance of a steep bank [8, Vol. 2, p. 287].

As the gist of this article was repeated in his *Elementary Illustrations* and in his encyclopaedia article on Tides, we henceforth discuss only the last. These are reprinted in volume 2 of Young's *Miscellaneous Works* [8], and we cite page references from the latter. According to Peacock, "Dr. Young was accustomed to regard his exposition of this theory of tides as nearly the most successful of his physico-mathematical labours, only second in importance to his researches on the theory of light" ([8, Vol. 2, p. 262, editor's note]).

In the introduction to his encyclopaedia article, Young misleadingly wrote:

> Laplace's computation is however limited to the case of an imaginary ocean, of a certain variable depth, assumed for the convenience of calculation, rather than for any other reason. Dr. Thomas Young has extended Laplace's mode of considering the phenomena to the more general case of an ocean covering a part only of the

earth's surface, and more or less irregular in its form; he has also attempted to comprehend in his calculations the precise effects of hydraulic friction on the times and magnitudes of the tides [8, Vol. 2, p. 292].

He continued with a summary of observations of the actual tides around the world, presenting a large table of times of high water at various stations, at "the full and change of the Moon", recorded versus their longitude. This clearly showed that "the line of contemporary tides is seldom in the exact direction of the meridian, as it is supposed … in the theory of Newton and Laplace" [8, Vol. 2, pp. 294–297]. Indeed, "the bending of the great wave round the continents of Africa and Europe seems to be very like the sort of refraction which takes place on every shelving coast with respect to the common waves" [8, Vol. 2, p. 299]. This is an acute observation, though not backed up by any calculations.

Young soon goes on to explore his analogy between the tides and forced pendulums. There, he incorporates the influence of frictional effects, already explored in his "Hydraulic Investigations". He first looks at free oscillations of a cycloidal pendulum with resistance proportional to the square of velocity. In modernised notation, small oscillations satisfy the differential equation

$$\frac{\mathrm{d}^2 s}{\mathrm{d}t^2} + Bs - D\left(\frac{\mathrm{d}s}{\mathrm{d}t}\right)^2 = 0,$$

where B and D are positive constants, s is the angular or horizontal displacement and t is time. But this equation holds only for the first swing, while $\mathrm{d}s/\mathrm{d}t$ is negative. For the next swing, when $\mathrm{d}s/\mathrm{d}t$ is positive, the sign of the D term must be reversed. Young makes heavy weather of even the first swing: he obtains a first integral, and then the first few terms of a series expansion for small D. He thereby finds, approximately, the time of the first swing. Reversing the sign of D gives the time of the reverse swing and their sum yields the time of one complete oscillation. His main finding is that the leading-order correction to the undamped period is an $\mathrm{O}(D^2)$ quantity.

Resistance proportional to the velocity is a lot easier, as the motion is governed by the linear equation

$$\frac{\mathrm{d}^2 s}{\mathrm{d}t^2} + A\frac{\mathrm{d}s}{\mathrm{d}t} + Bs = 0.$$

Competently enough, Young derives the general solution in two ways, first using complex exponentials, and then without (the latter no doubt in deference to those who remained suspicious of complex numbers), [8, Vol. 2, pp. 313–318].

With his analogy with tides in view, he then turns to forced oscillations, with periodic forcing of the form $M \sin Ft$ where M and F are constants. He successfully solves the resulting equations first without resistance and then with resistance proportional to the velocity. Then he shows how to deal with superpositions of forces of the form $M \sin Ft + M' \sin F't \ldots$ All this is elementary nowadays, and need not be described further.

Even without resistance, Young's pendulum analogy shed light on whether the tide is direct (i.e., in phase with the periodic disturbing force) or inverted (i.e., out of phase by 180 degrees). This depends on whether the natural period of unforced oscillations is less or greater than that of the disturbing force. Taking the tidal wavelength to equal half the Earth's circumference and the speed of waves to be $c = (gh)^{1/2}$ where h is the depth, a critical depth of about 13 miles (21 km) is found, the tides being direct for depths greater than this and inverted for less. Young also drew conclusions about the influence of resistance on the amplitudes and phases of the tides, relative to those of the perturbing forces, showing that resistance has a significant effect on the times of high water.

George Peacock was one who admired Young's work on tides, "though more for its bold intuitions than for its mathematical elegance"; see [1, p. 186]. In a footnote accompanying Young's analysis of pendulums, Peacock wrote that: "The methods adopted here make a bold and, in the circumstances being considered, a tolerably successful inroad upon the solution of a problem of great difficulty by means which are apparently hardly sufficient for the purpose" [8, Vol. 2, p. 275, editor's note]. In 1841, George Biddell Airy, the Astronomer Royal, wrote his own even more influential article "Tides and Waves" [34] for the *Encyclopaedia Metropolitana* without reading Young's work; but he later confessed to Peacock (who had been his tutor at Cambridge) "that in writing on *any* physical subject it is but ordinary prudence to look at him first." He further wrote:

> You ask my opinion of Dr. Young's researches on tides; as far as they go they are capital … When I came to look at him, I was surprised to find that he has clearly enough shown the difference of positive and negative waves, and also the differences of free oscillations and forced oscillations: and that he has hinted at the cause of the rapid rise of river tides as distinguished from their slower fall. All these were great points with me, quite original to myself. There is one of mine, however, which he has not got, namely, the effect of friction in producing an apparent retardation of the day of spring tides etc. [8, Vol. 2, p. 262, editor's note].

In fact, Young did consider this last topic. He explicitly stated that "the spring tides will be retarded or accelerated more than the neap tides; … and the highest tides will not be precisely at the syzygies, but may be before or after them, according to circumstances." But he admitted that the effect in some harbours "is observed in a greater degree than can well be explained from the present state of the calculation" [44, p. 223].

Later, Horace Lamb, in his famous treatise *Hydrodynamics* [45], gave due acknowledgment to Young's work exploring the analogy between pendulums and tides, and Lord Rayleigh was another who commended this; see [1, pp. 186–187]. On the other hand, Young's friend and biographer Hudson Gurney perceptively wrote that:

> There are some among the most distinguished of surviving English philosophers, who still think that his theory of the Tides rests too exclusively on analogies, and that many of the elements of the computation are too out of human reach to render the boldness of the original thought susceptible of being subjected to the severity of mathematical deduction [2, p. 35].

6 Surface tension: Young versus Laplace

Young's name is again coupled with that of Laplace in connection with the cohesion of fluids. The result

$$\Delta p = \gamma \left(\frac{1}{R_1} + \frac{1}{R_2} \right),$$

denoting the change in pressure across a fluid interface with surface tension coefficient γ and principal radii of curvature R_1 and R_2, is now familiar. This is often called the *Laplace equation* or *Young–Laplace equation*. Young's name is also associated with the condition

$$\gamma_{LV} \cos \lambda = \gamma_{SV} - \gamma_{SL}$$

relating the three interfacial tensions γ_{SV}, γ_{LV}, γ_{SL} at the intersection of solid/air, liquid/air and solid/liquid boundaries, where the solid is locally plane and λ is the contact angle between the liquid and solid. This is sometimes called *Young's equation* or the *Young–Dupré equation* [46]. It was Young who first proposed a constant contact angle at such an intersection, and he discussed the values of this angle for various media. But he would surely have regarded the so-called "Young–Dupré equation" as trivially obvious, for it simply expresses the equilibrium of forces along the direction of the solid plane. In contrast, the attribution of the former result was one that Young cared about, and which brought him into conflict with Laplace.

Young had first stated this result in 1805 in his "An Essay on the Cohesion of Fluids" [47] in the *Philosophical Transactions of the Royal Society of London*, and it was derived by Laplace a year later, in a supplement to Book 10 in the fourth volume of his *Mécanique céleste* [21]. In the words of one modern authority, Young then reprinted his paper "with additions and with some unwarranted criticisms of Laplace's first paper in *Lectures on Natural Philosophy*, **2**, p. 649… and in *Miscellaneous Works* … **1**, p. 418. Young obtained [the result] but characteristically put it into words, not as an equation" [48, p. 22, note 20].

Young's statement is as follows:

> It is well known, and it results immediately from the composition of forces, that where a line is equally extended, the force that it exerts, in a direction perpendicular to its own, is directly as its curvature; and the same is true of a surface of simple curvature; but when the curvature is double, each curvature has its appropriate effect, and the joint force must be as the sum of the curvatures in any two perpendicular directions. For this sum is equal, whatever pair of perpendicular directions may be employed [8, Vol. 1, p. 419].

No mathematics whatsoever appeared in Young's original article, but the second volume of his published *Lectures* of 1807 [9] incorporated a mathematical insertion by Young that his later editor, George Peacock, deemed "unduly concise and obscure": this is repeated in [8, Vol. 2, pp. 420–422]. He had also added a new section [8, Vol. 2, pp. 436–453] containing a hostile critique of Laplace's 1806 essay, which gave "results nearly similar to those which are contained in this paper." Regarding some criticisms by Laplace of a passage in Isaac Newton's *Optics*, Young acidly remarked that:

> Mr. Laplace's superior skill in the most refined mathematical investigations might perhaps have enabled him to make still more essential improvements, if it had been employed in some other subjects of natural philosophy; but his explanation of these phenomena being exactly the same as that which I had already published, in an essay not containing … any one mathematical symbol, it is obvious that the inaccuracy of Newton's reasoning did not depend upon any deficiency in his mathematical acquirements [8, Vol. 2, pp. 444–445].

He admits that:

> … in this country, the cultivation of the higher branches of the mathematics, and the invention of new methods of calculation, cannot be too much recommended to the generality of those who apply themselves to natural philosophy; but it is equally true, on the other hand, that the first mathematicians on the continent have exerted great ingenuity in involving the plainest truths of mechanics in the intricacies of algebraical formulas, and in some instances have even lost sight of the real state of an investigation, by attending only to the symbols, which they have employed in expressing its steps [8, Vol. 2, p. 453].

In contrast with Young's statement, entirely in words, of a result that he regarded as "well known", Laplace gave its mathematical derivation [21] (supplement to Book 10, 1806) in a form that most would nowadays consider necessary. But there is no denying Young's brilliant insight. Arguably, the result *is* physically obvious for a curved elastic line (and it must be remembered that Young had thought long and hard about bending beams), but less so for surfaces of double curvature. And Young's observation that the sum of the curvatures in any two perpendicular directions is always equal to the sum of the two principal curvatures is certainly based on a mathematical calculation (generally attributed to Euler), rather than physical insight.

In view of Young's interest in water waves, it now seems surprising that he did not consider the influence of surface tension on those of short wavelength. But neither did he consider gravity waves in deep water or in arbitrary depth, for which the theory was first given by Poisson in 1818 (with an earlier "near miss" by Laplace in 1776): see [17]. The first to give the theory of capillary-gravity waves seems to have been William Thomson (Lord Kelvin), in a paper of 1871 [49], with earlier observations of such waves by John Scott Russell in 1845: see Darrigol [36, pp. 59, 88].

But, for both Young and Laplace, the derivation (or assertion) of the "Young–Laplace formula" was not the main point of their studies. Rather, they were trying to develop a general theory of cohesion of fluids, based on speculations about the nature of short-range inter-particle forces acting throughout the fluid. These attempts are interesting as early approaches to molecular theories of matter, but only the "Young–Laplace formula" that results from these theories is central to the fluid mechanics of media assumed to be continuous. The assumptions of Young and Laplace differed: whereas Young considered fluid particles to be held in equilibrium by a balance of short-range attractive (or "contractile") and repulsive forces, with the former acting over smaller distances than the latter, Laplace considered only attractive forces. But, in both cases, the net effect was that the surface behaved as if it possessed elasticity, so giving the "Young–Laplace formula". A full history of this topic is given by Bikerman [50] and Rowlinson [51].

As just mentioned, Young returned to the subject of "cohesion" in his Royal Institution lectures [9] (Lecture L), drawing much of the material from his 1805 paper [47] but surprisingly omitting any mention, even in words, of the "Young–Laplace formula". Instead, he refers to his earlier Lecture XIII "On passive strength and friction", which is a masterly account of elasticity and the strength of materials: though as always expressed without any formulae, he emphasises the connection between applied forces and induced curvature. Less creditably, in Lecture LX "On the history of terrestrial physics", Young criticises Laplace's memoir on cohesion and capillary tubes, alleging that: "as far as he has pursued the subject, he has precisely confirmed the most obvious of my conclusions; although his mode of calculation appears to be by no means unexceptionable, as it does not include the consideration of the effects of repulsion" [10, Vol. 1, p. 589]. Also, as already noted, the second volume of his *Lectures* contained the revised reissue of his 1805 paper, with further harsh words about Laplace. Though not in Kelland's second edition [10], this is reproduced in Young's *Miscellaneous Papers* [8].

Young returned to the topic in a thirty-page article on "Cohesion", written in 1816 for the *Supplement* to the *Encyclopaedia Britannica* [52], arguing for the superiority of his model based on both repulsive and attractive forces, and repeating his unconvincing attempt at a mathematical derivation. He also states a version of the "Young–Dupré equation" in which he (wrongly) conjectures that the contractile forces are related to the differences in densities of the adjacent media [8, Vol. 1, p. 464]. Then he calculates the forms of several surfaces of simple and double curvature, in part by employing series expansions: for these, he claims good agreement with some experiments conducted by others. He also gave a brief account of his theory in Appendix A of his *Elementary Illustrations* [20, pp. 329–337], with no mention of Laplace.

Volume 4 (1820) of the same *Supplement* contains another article on a closely related topic, written by James Ivory and entitled "Fluids, Elevation of". (This immediately follows another of Young's articles, on "Fluents", a lengthy compilation of integrals of functions culled mainly from a German work by M. Hirsch.) In Ivory's view,

> The formula of Laplace must be considered as a great step made in this branch of natural philosophy, not only because it ascertains the connection between the pressure and the curvature, in which it agrees with the hypothesis of Segner and Dr. Young, but also because it brings into view the forces K and H [in Laplace's version of the "Young–Laplace formula"], and draws attention to the relation they have to one another, and to the primitive attraction of the particles [53, p. 326].

Young was most displeased to see his result described as a mere hypothesis, and credit for the theory given solely to Laplace: the resulting controversy is briefly discussed in [23, pp. 231–232].

Finally, one should mention the influence of this work on the later evolution of molecular physics. The kinetic theory of gases and the theory of capillarity both indicated how a molecular theory of matter might be constructed, and James Clerk Maxwell, for one, studied the latter as well as the former: for these later developments, see [51,54]. It was Clerk Maxwell who wrote a classic article on surface tension, with full historical summary, for the ninth edition of *Encyclopedia Britannica*, and it was Lord Rayleigh, another admirer of Young, who revised it for the tenth edition.

7 Discussion

Despite some valid criticisms, Thomas Young's high reputation as a gifted polymath who made fundamental contributions to science, medicine and the humanities, is unassailable. His deep physical insight and inventive speculations particularly enriched several areas of physics. Though his contributions to fluid mechanics were less spectacular than those in some other areas, his work on waves and tides, and especially his fruitful analogies with the motion of pendulums, had a lasting impact on later scholars. Similarly, his pioneering insights on surface tension, though overtaken by Laplace's analytical demonstration, well deserve the recognition that they have received. In contrast, his work on the resistance of flow through tubes and pipes is long forgotten, and has flaws noted above. But he should be commended for making the first, though incomplete, attempt at a theory of the hydraulic jump or bore, and for his observations of jets of air that clearly show transition to turbulence.

Young was happiest, and best, in the role of a speculative natural philosopher. Though a competent experimenter, he admitted a reluctance to spend the time necessary to make a first-class experiment. As a mathematician, he was competent but not brilliant, adhering when he could to outdated geometrical modes of thought, and impatient with what he saw as excessive proliferation of symbols in analysis. In some of his writings, he took this aversion to ideological excess, publishing his Royal Institution *Lectures* and several papers without using a single formula or equation, although their use would have clarified his many elaborate circumlocutions. But there too his sound physical insights shine through the verbiage. It is a considerable irony that he chose to expound Laplace's *Mécanique* *céleste*, as Laplace was a diametrically opposed ideologue, so convinced of the primacy of analysis that he avoided all diagrams and geometrical arguments.

It is hard to identify the major influences on Young's scientific views. Essentially, he was a voracious reader who educated himself, rather than one who was instructed by others. The authors of many books and papers were his teachers, and the Catalogue published in [9, Vol. 2] shows the incredible breadth and depth of his reading. But one whose influence he expressly acknowledged was John Robison of Edinburgh. In the Preface to his *Syllabus* [11], he mentions "the extensive use that has been made of the valuable articles contributed by Professor Robison to the Encyclopaedia Britannica", and Robison is one of the most frequently cited authors in his *Lectures* [9]. It is worth noting that he almost certainly met Robison while studying in Edinburgh, and that Robison was another who expounded physical subjects with minimal use of mathematics. It is also noteworthy that he spent time in Göttingen as a student, when he travelled around the German states; that he visited Paris for two weeks in 1802, when he attended discussions at the National Institute;[5] and that he finally got to Italy in 1821, after the Napoleonic wars that had curtailed travel in Europe; see [1].

It is equally hard to identify later scholars who were directly influenced by Young. His lectures at the Royal Institution would have won few converts; but his set-piece lectures to the Royal Society, on optics and blood flow, must have commanded attention, and were later published in the *Philosophical Transactions*. In due course, the wave theory of light became the orthodox view, espoused by G.B. Airy and later by G.G. Stokes. But, surprisingly, Airy had not read Young's long encyclopaedia article on Tides when he prepared his own. Young's many published papers were no doubt read, and there were polemical exchanges with rivals who held differing views. His involvement with the Royal Society, as Foreign Secretary and as a member of other committees, certainly brought him into contact with most of the major British—and some foreign—scholars of his day. Yet there is no-one who can be identified as a disciple of Young, and in his lifetime he seems to have been a rather remote, though respected, figure.

Where applied mathematics is concerned, Young's reputation is at best equivocal, and he is a frustrating author to read. He had a keen eye for identifying interesting problems, he made many sound speculations, and he explored instructive analogies; but his mathematical skill was often inadequate to accomplish his aims, and his mathematical style is even more off-putting to modern eyes than to those of his contemporaries. Commenting on Young's seminal "Essay on the Cohesion of Fluids" [45], his friend Hudson Gurney wrote that:

> The mathematical reasoning, for want of mathematical symbols, was not understood, even by tolerable mathematicians; from a dislike of the affectation of algebraic formality, which he had observed in some foreign authors, he was led into something like an affectation of simplicity, which was equally inconvenient to the scientific reader [2, p. 54].

Acknowledgments I am grateful to Mark Cooker for inviting me to contribute this tribute to the late Howell Peregrine. I also thank Olivier Darrigol for several pertinent questions and observations, and Ivor Grattan-Guinness and three referees for comments on earlier drafts. The assistance of Peter Lindsay and of St Andrews University Library Special Collections with the figures is also gratefully acknowledged.

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