Science Education and the Scientific Revolution: a way to learn about Science

MICHAEL R. MATTHEWS

School of Education, University of New South Wales
Australia
m.matthews@unsw.edu.au

ABSTRACT

This paper documents some of the international curriculum documents that require that science students learn about science –its methodology, relations with wider culture, technology and worldviews– as well as learning the content and process skills of science. This wider, or cultural, goal for science courses amounts to students learning something about the history and philosophy of their subject. It is argued that some study of the Scientific Revolution is a very appropriate and rich way to forward this cultural goal. The example of the seventeenth-century debate about the shape of the earth is used to illustrate significant features of the scientific revolution, and consequently enduring features of modern science.

KEY WORDS

Science education, scientific revolution, history and philosophy of science and education

RÉSUMÉ

Cette étude documente la conception selon laquelle certains curricula internationaux en sciences physiques doivent offrir aux élèves la possibilité d'apprendre non seulement leurs contenus et savoirs-faire mais aussi quelques éléments sur les sciences physiques-leur méthodologie, leurs relations avec la culture et la technologie. Cet objectif culturel signifie que les élèves devraient apprendre quelque chose sur l'histoire et la philosophie des sciences physiques.

Dans cet article il est soutenu que l'étude de la Révolution Scientifique est un moyen approprié pour avancer cet objectif culturel. La discussion sur la forme de la terre qui a été développée pendant le 17ème siècle exemplifie quelques caractéristiques importants de la période de la Révolution Scientifique qui sont, d'ailleurs, caractéristiques permanents des sciences physiques contemporaines.

MOTS CLÉS

Didactique des sciences physiques et naturelles, révolution scientifique, histoire et la philosophie des sciences physiques

INTRODUCTION

A common feature of contemporary science education curricula is the expectation that as well as learning science content, students will learn something *about* science. For example the American Association for the Advancement of Science expressed this position in its *Project 2061* publication: «…*Becoming aware of the impact of scientific and technological developments on human beliefs and feelings should be part of everyone's science education*» (AAAS, 1989, p. 173). The position was elaborated a year later in *The Liberal Art of Science*: «*The teaching of science must explore the interplay between science and the intellectual and cultural traditions in which it is firmly embedded. Science has a history that can demonstrate the relationship between science and the wider world of ideas and can illuminate contemporary issues*» (AAAS, 1990, p. xiv). I have elsewhere expressed the point as follows: If students do not learn and appreciate something *about* science –its history, its interrelationships with culture, religion, worldviews and commerce, its philosophical and metaphysical assumptions, its epistemology and methodology– then the opportunity for science to enrich culture and human lives is correspondingly minimized. If science is taught merely as a technical subject devoid of its cultural and philosophical dimensions, then the positive results of science education are less able to fructify in society (Matthews, 1994).

Having students examine the Scientific Revolution is a most engaging and fruitful way to realise this cultural goal of science education; it is a manageable way for students to learn *about* science. Most human endeavours and engagements are better understood if their origins are understood. This is a form of 'genetic principle' in social affairs. For example, people are better understood if something is known of their upbringing and family life – a commonplace developed *in extremis* by psychoanalysis. Institutions such as churches and political parties are better understood if something of their origins is known. Understanding conflict in the Middle East, in Northern Ireland, in Afghanistan requires some knowledge of their historical-political origins. So too with modern science: a proper appreciation of the scientific tradition involves some understanding of where it began, and this basically means the milieu, personalities, methodologies and accomplishments of the seventeenth-century Scientific Revolution in western Europe.

THE REVOLUTIONARY MOMENT

Although one of the greatest, if not *the* greatest achievement of human endeavour, the Scientific Revolution itself was a mere blink in human history. Galileo's *Two Chief World Systems* was published in 1633, followed by his *Two New Sciences* in 1638, and Newton's *Principia* was published in 1687. So a mere 50 years separated what might provisionally be taken as the book-ends of the revolution.

There has of course been energetic debate about the extent to which the Scientific Revolution was truly revolutionary. This debate commenced with the publication of Pierre Duhem's *Le Système du monde* in the early years of the twentieth century (Duhem, 1908/1969). He wrote against Ernst Mach and the then dominant «revolutionary» or «discontinuity» reading of the scientific achievements of the seventeenth century. Following Duhem a number of historians and philosophers further developed the 'continuity' thesis, linking the New Science to precursors in the Middle Ages and Renaissance. Among the more prominent were Ernest Moody (1951, 1966), John Herman Randall Jr. (1940), Anneliese Maier (1982) and William Wallace (1981). These variously maintained that the Galilean-Newtonian revolution was conceptually prepared for by late medieval natural philosophers. The 'continuity' theorists draw particular attention to the work of the fourteenth century Parisian scholastics and the sixteenth century Roman Jesuits.

And there is on-going inquiry into what enabled the localised revolution in isolated centres in Western Europe to spread and win adherents across all of Europe and eventually across the world. Was it the strength of ideas? Was it the strength of arms? Was it the better serving of technical and commercial interests? These questions raise important issues concerning not only the rationality of science, but the role reason in the spread, communication or diffusion of science[1].

But these scholarly debates need not be settled here: everyone agrees that matters of great scientific (natural philosophy) significance occurred in Western Europe in the seventeenth century, and that Galileo and Newton were centrally involved. One can date the beginning a little earlier –perhaps with Gilbert's *De Magnete* (1600), or Bacon's *The New Organon* (1620) or Harvey's *The Circulation of Blood* (1628); and the end a little later– perhaps with Newton's *Optics* (1704) – but not withstanding some stretching, the

---

[1] See contributions to Porter and Teich (1992).

‘birth pangs’ of the New Science were not prolonged, they lasted no more than the lifespan of an average individual. Brief though its seventeenth-century birth was, modern science quickly grew up and has since been a dominating presence in the world.

SCIENTIFIC ACHIEVEMENTS OF THE REVOLUTION

The early or foundational achievements in modern science were monumental. In *magnetics*, a credible account of the compass and of «mother earth» as a huge lodestone was given by Gilbert. In *astronomy*, the heliocentric theory of the solar system was articulated and defended by Galileo, with enormous mathematical and observational skill the elliptic path of planets was described by Kepler, and comets were identified as commonplace celestial objects and their regular orbits calculated by Newton and his followers. In *mechanics*, the long-standing problems of free fall and projectile motion were solved by Galileo and Huygens, the laws of motion formulated, and Newton’s great synthesis of terrestrial and celestial mechanics was achieved. In *optics*, the composite nature of white light was revealed and basic properties of reflection and refraction were understood by Newton and Huygens. In *physiology*, the circulation of blood and the role of the heart were understood by Harvey. In *pneumatics* the existence of the vacuum and the operation of air pressure were understood by Torricelli and Pascal. In *chemistry*, the break with alchemy was initiated and the idea of elements established by Boyle and others. In *horology*, timekeeping was perfected by Huygens’ utilisation of the pendulum regulator, and the principle of the chronological method for solving the longitude problem was accepted. In *microscopy*, the cellular structure of plants, the profusion of micro-organisms in water and the existence of sperm cells ‘animalcules’ were demonstrated by Van Leeuwenhoek and Hooke. These endeavours in Natural Philosophy were institutionalised with the establishment of The Royal Society in England (1660) and the *Académie Royal des Sciences* in France (1666)[2].

THE SHAPE OF THE EARTH AND THE SHAPE OF THE NEW SCIENCE

The foregoing are just some of the important achievements of early modern science. In order to gauge the impact of these achievements on «learned opinion» at the time, it is useful to elaborate an example. So much of what was achieved in the half-century

---

[2] The achievements of the Scientific Revolution can be read in numerous «classic» works such as Butterfield (1949), Hall (1962) and Westfall (1977); and in more recent works such as Gribbin (2002, Book 2). A good guide to the massive literature on the Scientific Revolution is Cohen (1994).

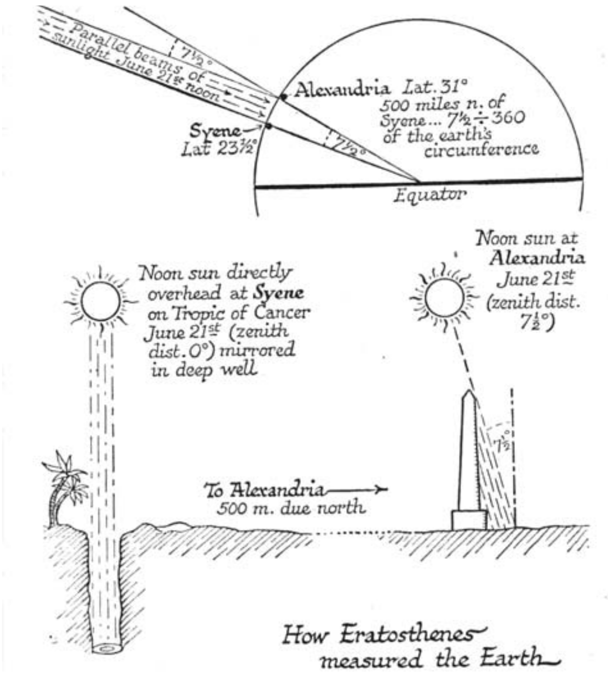
«blink» between the major works of Galileo (1638) and Newton (1687) is now so much a part of 'common knowledge' that the sense of achievement and admiration that, at the time, greeted the discoveries is difficult to recapture. But something of this impact needs to be recaptured in order to appreciate the effect that the New Science had on European intellectual and cultural life in the seventeenth century, and also in order to appreciate the continuing impact of the, then, New Science on subsequent European and world intellectual life.

An excellent example to elaborate is the onset and resolution of debate about the shape of the earth – the discipline of Geodesy. More specifically, this is an appropriate example because it engaged the attention of some major Enlightenment figures –Voltaire, D'Alembert and Maupertuis– who from it drew characteristically 'enlightened' lessons for the pursuit of all knowledge.

Ancient Views

Homer in the 8th century BC wrote of the earth as a plate surrounded by the river Oceanus. Three hundred years later the Pythagoreans were confident that the earth

FIGURE



Eratosthenes Measurement of the Earth (Hogben 1938, p. 83) was spherical. Aristotle and the major Greek thinkers shared this belief. They recognised that the earth's shadow cast on the moon during eclipses is always circular, that different stars are seen when travelling north or south, and that the top of approaching ships' masts are seen before the ship's body.

Famously Eratosthenes, the Alexandrian librarian, not only shared the belief but by measuring the different angle of inclination of sunlight at two towns along the meridian - Alexandria and Syene in Egypt – and the distance between these points was able in the second century BC to ascertain the diameter and circumference of the earth (Matthews 2000, p. 19-21). He determined the latter to be 39,690 km (in modern units) which compares remarkably well with its now known length of 40,000 km.

During the two thousand years between Aristotle and Galileo the spherical earth assumption was simply a given for physical geography and astronomy. Copernicus in 1543 displaced the earth from the centre of the solar system, but he did not question its sphericity, nor did Galileo or Kepler. Bad enough that the earth was no longer at the centre; it was unimaginable that God's creation on which the whole drama of Salvation History was being played, would be a less than perfect shape.

Timekeeping and the shape of the Earth

The overturning of this entrenched assumption was dependent upon one immensely important achievement of the Scientific Revolution, namely Galileo's discovery of the properties of pendulum motion – that period was independent of mass, independent of amplitude of swing, that it was isochronous and that it varied as the square root of length. Huygens refined Galileo's account of pendulum motion – showing geometrically that the cycloid, not the circle was the isochronous path, and that period was invariant only for small amplitude displacements (less than 5°). He then utilised the isochronous property of a small-amplitude, cycloidal pendulum to regulate clockwork (Matthews, 2000). With the adoption of the pendulum regulator the best clocks, 'overnight', increased in accuracy from 15-30 minutes a day to one minute a day with Huygens' 1657 clock and shortly after to one second per day with Graham's 1721 pendulum clock (Matthews, 2000, p. 177-180).

Huygens assumed, as did everybody else, a spherical earth and thus a constant force of gravitational attraction at all points over the earth's surface – the distance from the earth's centre being constant. Given this assumption, in 1673 he ingeniously proposed the length of a seconds pendulum to be the much-needed international unit of length (Matthews, 2000, p. 141-150). He believed that no matter where on earth a pendulum was taken if, for small oscillations, it beat in seconds (a period of two seconds) its length would be constant, and this could be the international length standard. It would be natural, portable, replicable, cheap and reliable (in Paris the length of Huygens' seconds pendulum was nearly what was later to become one metre, 0.997m). Such a standard would revolutionise commerce, trading, armaments, building and not least science.

But within a few years of proposing the standard Huygens abandoned it because the underlying sphericity assumption was proved false: the earth was not a perfect sphere, it was a deformed one, and so the force of gravitational attraction was not constant across its surface. That this entrenched assumption was disproved four hundred years before astronauts were able to look back on earth from space is a triumph of the New Science and something from which Enlightenment philosophers drew lessons. What triggered the disproof was an accidental time-keeping observation, in a far-away place, by Jean Richer, a young student member of the recently established A*cadémie Royale des Sciences*.

Under the directorship of Jean-Dominique Cassini (1625-1712), the A*cadémie* commissioned Richer to voyage was to Cayenne to ascertain the value of solar parallax and to correct the tables of refraction used by navigators and astronomers. A secondary consideration was checking the reliability of marine pendulum clocks which were being carried for the purpose of establishing Cayenne's exact longitude (Olmsted, 1942). Cayenne was in French Guiana, at latitude approximately 5A N. It was chosen as a site for astronomical observations because equatorial observations were minimally affected by refraction of light passing through the earth's atmosphere – the observer, the sun and the planets were all in the same plane.

The voyage was spectacularly successful in its primary purposes: the obliquity of the ecliptic was determined, the timing of solstices and equinoxes was refined and, most importantly, a new and far more accurate value for the parallax of the sun was ascertained – 9.5» of arc. This figure –equivalent to the angular size of the earth's radius when viewed from the sun– provided the only known way to measure the distance of the sun from the earth, and hence the dimensions of the solar system. Using Richer's parallax figure, Cassini calculated the sun to be 21,600 semi earth-diameters (87,000,000 miles) from the earth – the contemporary estimate is 92,800,000 miles. The thus revealed enormity of the solar system was staggering to contemporaries, especially to non-astronomers. Voltaire thought that the earth, and man's place on it, had been shrunk to insignificance. For believers, adjusting to Copernicus's displacement of God's chosen and redeemed people from the centre of the universe had been difficult enough; many baulked when asked to accept a ninety-odd million mile displacement from the centre.

But it was the unexpected consequences of Richer's voyage which destroyed Huygens' vision of a universal standard of length 'for all nations' and 'all ages', and along with it the long-cherished assumption of a spherical earth. Richer found that a seconds pendulum-clock that was set up in Paris so that it recorded the passage of exactly 24 hours between one astronomical noon reading and the successive noon reading, took only 23 hours 57 minutes and 32 seconds between noon readings at Cayenne; the clock lost 2½ minutes daily. Richer saw that the Paris clock had to be shortened in order to swing in seconds at Cayenne, not much, 2.8 mm (0.28%), but nevertheless shortened[3]. This was tantamount to saying that the force of gravity, and hence the weight of bodies, diminished from Paris to the equator – an astonishing conclusion[4].

Replacing a scientific theory

Although establishing the fact that a pendulum clock slowed in equatorial regions was itself an impressive achievement –given the technology and degrees of precision required for the measurements– it did not immediately disprove the spherical earth theory. Huygens and other holders of the spherical earth theory could legitimately maintain their belief in the face of the slowing of the pendulum clock. How this was done illustrates nicely some key methodological matters about science, and about theory testing.

Given the spherical earth theory (T), and the assumption that gravity alone affects the period of a constant length pendulum, the observational implication was that the pendulum's period at Paris and the period at Cayenne would be the same (O). Thus:

$$T \rightarrow O$$

But Richer seemingly found that the period at Cayenne was longer, the clock slowed, (~ O). Thus, on simple, Popperian, falsificationist views of theory testing:

$$T \rightarrow O, \sim O, \therefore \sim T$$

But theory testing is never so simple – a matter that was recognised by Popper, and articulated by Kuhn (1962), Lakatos (1970), Feyerabend (1975) and a host of other contemporary philosophers of science. In the seventeenth century, many upholders of

---

[3] Richer's demonstration raised the problem of an independent measure of time. He did not have a second timepiece (a digital watch, for instance) against which to measure the speeding up or slowing down of his pendulum clock. The only independent clock he had was the clock of the heavens. He probably measured the number of pendulum swings against the number of seconds in a solar day (noon to noon) or a sidereal day. This was a difficult enough technical exercise, and it was compounded by the fact that the solar day actually varies in length by plus or minus 15 minutes through the year. But the yearly variation, the Equation of Time, was known, and the technical problems of timing the sun's transit were overcome.

[4] The fact that the weight of a body changed from place to place, as was manifest in the variation of the pendulum's period, sowed the seed for the conceptual distinction between weight and mass. The intuition was that although weight changed with change in gravity, nevertheless something about the «massiness» of the body remained the same. Jean Bernoulli first introduced the distinction between mass and weight, and Newton clarified it by introducing the idea of inertial mass.

T just denied the second premise, ~O. The astronomer Jean Picard, for instance, did not accept Richer's findings. Rather than accept the message of varying gravitation, he doubted the messenger. Similarly Huygens was not favourably disposed towards Richer. In 1670, on one longitude testing voyage to the West Indies and Canada, Richer had behaved irresponsibly with regard to Huygens' clocks – he did not immediately restart them when they stopped in a storm, and finally he allowed them to crash to the deck (Mahoney, 1980, p. 253). Huygens did not require much convincing that it was Richer's ability, not gravity that was weak at Cayenne. But when more and more messengers arrived from different equatorial regions, the slowing of the equatorial pendulum was finally accepted as a scientific fact.[5] It was accepted by Huygens and by Newton who wrote in 1682 that: «*Monsr. Richer sent by y*^{e} *French King to make observations in the Isle of Cayenne (North Lat 5*^{gr}*) having before he went thither set his clocke exactly at Paris found there in Cayenne that it went too slow as every day to loose two minutes and a half for many days together and after his clock had stood & went again it lost 2½ minutes as before. Whence Mr Halley concludes that y*^{e} *pendulum was to be shortened in proportion of – to – to make y*^{e} *clock true at Cayenne. In Gorea y*^{e} *observation was less exact*» (Cook, 1998, p. 116).

Still the spherical earth theory could be saved. Huygens and others saw that theories did not confront evidence on their own, there was always an 'other things being equal' assumption made in theory test; there were *ceretis paribus* clauses (C) that accompanied the theory into the experiment[6]. These clauses characteristically included statements about the reliability of the instruments, the competence of the observer, the assumed empirical state of affairs, theoretical and mathematical devices used in deriving O, and so on. Thus:

$$T + C \rightarrow O, \sim O, \therefore \sim T \text{ or } \sim C$$

Huygens and others maintained belief in T, and said that the assumption that other things were equal was mistaken – humidity had slowed the swings, heat had lengthened the pendulum, friction increased in the tropics, and so on. These were legitimate concerns, but each was independently controlled for and tested, and still the pendulum clock had to be shortened in equatorial regions.

Still there was one last defence for the spherical earth. Holders of T said that because the earth was spinning, then there was a centrifugal force 'throwing' bodies off the earth. This was zero at the poles – there was no tendency to be thrown off – and increased to a maximum at the equator. Hence at all places on the earth's surface the resultant downwards force on a body was the force of gravity (acting down) less

---

[5] Fleck (1935/1979) is the classic work on the establishment of scientific facts.

[6] For discussion of this matter see Earman, Glymour & Mitchell (2002).

the centrifugal force (pulling outwards). So effective gravity was reduced at the equator and it was this that resulted in the pendulum slowing, as period was inversely proportional to g.

This qualitative argument would be sufficient for uncritical holders of T, it seemed to save the theory, but it was not sufficient for Huygens or Newton. Huygens calculated what the diminished force of gravity would be at the equator, and hence the resultant increase in period, and thus the amount of shortening required to compensate for the increase. Richer had determined that approximately 3 mm shortening was needed for the Paris pendulum to continue to beat seconds at Cayenne. Huygens worked out that the effect of the centrifugal force resulting from the earth's spinning. The mathematical calculation for determining apparent diminution in g is easily done:

At the equator a body rotates through 360 degrees or 2π radians per day (8.6×10^4 seconds). So the angular velocity $\acute{\omega} = 2\pi / 8.6 \times 10^4$ radians per second (7.3×10^{-5} rads/sec). And centripetal acceleration at Cayenne, a_c , is given by $a_{c\,=} \acute{\omega}^2 r$. And r (the earth's radius) is 6.4×10^6 metres. Thus $a_{c\,=} \acute{\omega}^2 r = 0.034$ m/sec^2.

So the effect of a spinning earth at Cayenne was to decrease the Parisian gravitational attraction (assuming a spherical earth) by 0.034 m/sec^2. From the formulae for the period of a simple pendulum, $T = 2\pi\sqrt{\ell/g}$ it follows that if we keep T constant (2 seconds, as Richer did). Then from a change in g we can determine the corresponding change required in l, by the formulae $g_l = g_o l_l / l_o$[7].

The Earth moved by a match

Accordingly, Huygens determined that a shortening of 1.5mm was required to make up for the spinning earth effect. But this left 1.5 mm not accounted for. This is less than the thickness of a match, yet for such a minute discrepancy Huygens, and Newton,[8] were prepared to abandon the spherical earth theory and claim that the true shape of the earth was an oblate – the earth bulged at the equator and was flattened at the poles.

The Richer episode did not escape the attention of Voltaire, a champion of Newtonian science and a key figure in the European Enlightenment who, in 1738 wrote: «*At last in 1672, Mr Richer, in a Voyage to Cayenna, near the Line, undertaken by Order of Lewis XIV under the protection of Colbert, the Father of all Arts; Richer, I say, among many Observations, found that the Pendulum of his Clock no longer made its Vibrations so frequently as in the Latitude of Paris, and that it was absolutely necessary to shorten it by a*

---

[7] For the physics and mathematics of these calculations see Holton & Brush (2001, p. 128-129).

[8] In his *Principia* (Bk.III, Prop.XX, Prob.IV), Newton utilised Richer's, and Halley's comparable observations from St. Helena, to develop his oblate account of the Earth's shape.

Line, that is, eleventh Part of our Inch, and about a Quarter more. Natural Philosophy and Geometry were not then, by far, so much cultivated as at present. Who could have believed that from this Remark, so trifling in Appearance, that from the Difference of the eleventh of our Inch, or thereabouts, could have sprung the greatest of physical Truths? It was found, at first, that Gravity must needs be less under the Equator, than in the Latitude of France, since Gravity alone occasions the Vibration of a Pendulum. In Consequence of this it was discovered, that, whereas the Gravity of Bodies is by so much the less powerful, as these Bodies are farther removed from the Centre of the Earth, the Region of the Equator must absolutely be much more elevated than that of France; and so must be farther removed from the Centre; and therefore, that the Earth could not be a Sphere» (Fauvel & Gray, 1987, p. 420). He dryly commented that: «*Many Philosophers, on occasion of these Discoveries, did what Men usually do, in Points concerning which it is requisite to change their Opinion; they opposed the new-discovered Truth*» (Fauvel & Gray, 1987, p. 420).

Voltaire and proponents of the Enlightenment thought that the way that the Shape of the Earth debate was resolved could be emulated in other fields of hotly contested debate and disagreement – especially in politics, religion, ethics and law – and instead of doing what 'Men usually do' in these fields, they would do what the natural philosophers did.

THE ONSET OF ENDURING THEMES IN MODERN SCIENCE

The Shape of the Earth debate is an illuminating episode that illustrates a number of themes that characterise the history of modern science:

1. The communitarian nature of scientific advances. Newton acknowledged this when he spoke of «standing on the shoulders of giants». Huygens calculations likewise depended on the achievements of Richer, and of Eratosthenes and later Cassini who provided increasingly accurate estimates of the radius of the earth.
2. The dependence of science upon technology. The final acceptance of Richer's pendulum slowing as a scientific fact required confidence in the accuracy and reliability of the clock makers, and the dependability of telescope makers whose instruments were used to ascertain successive noons or star transits. Without confidence in the accuracy and reliability of instruments, Richer's findings could just be put down to experimental error, and the spherical earth theory thus retained. The episode signals the move to a «world of precision» that would thereafter characterise modern science.
3. The dependence of science upon mathematics. It was only when Huygens worked out the quantitative effect of the spinning effect on equatorial pendulum length that he was able to see that there still remained a 1.5mm discrepancy to account for. Without the mathematics that enabled the radius of the earth to be calculated, and

the mathematics that enabled the spinning effect to be quantified, there would be no reason to challenge the spherical earth assumption.

4. The centrality of a critical outlook. Huygens rigorously defended his seconds pendulum as a universal standard of length, and consequently the spherical earth theory, but when contrary evidence accumulated he not only recognised it, but added to it, and modified his theory.

Many other episodes in the Scientific Revolution can be chosen by teachers to illustrate these, and perhaps other, general themes.

CONCLUSION

When students study science in schools they are being initiated into a tradition of scientific thinking, language, competences and knowledge claims. This initiation should be conscious rather than unconscious, critical rather than uncritical, historical rather than ahistorical, rich and engaging rather than barren and alienating. Inadequate understanding of traditions is one of the things that give rise to fundamentalisms of all sorts – religious, political and scientific. Where curricula encourage students to learn *about* science as well as learning the content of science, then a suitable introduction to the personalities, achievements and methodologies of the Scientific Revolution is an ideal way for this to be realised.

REFERENCES

American Association for the Advancement of Science (AAAS) (1989). *Project 2061: science for all Americans* (Washington DC: AAAS).

American Association for the Advancement of Science (AAAS) (1990). *The liberal art of science: agenda for action* (Washington DC: AAAS).

Butterfield, H. (1949). *The Origins of Modern Science 1300-1800* (London: G. Bell & Sons).

Cohen, H. F. (1994). *The scientific revolution: a historiographical inquiry* (Chicago: University of Chicago Press).

Cook, A. (1998). *Edmond Halley: Charting the Heavens and the Seas* (Oxford: Clarendon Press).

Duhem, P. (1908/1969). *To Save the Phenomena: An Essay on the Idea of Physical Theory from Plato to Galileo* (Chicago: University of Chicago Press).

Earman, J., Glymour, C. & Mitchell, S. (eds) (2002). *Ceterus Paribus Laws* (Dordrecht: Kluwer Academic Publishers).

Fauvel, J. & Gray, J. (eds) (1987). *The history of mathematics: a reader* (London: Macmillan).

Feyerabend, P. K. (1975). *Against Method* (London: New Left Books).

Fleck, L. (1935/1979). *Genesis and development of a scientific fact* (Chicago: University of Chicago Press).

Gribbin, J. (2002). *Science: a history 1543-2001* (London: Penguin Books).

Hall, A. R. (1962). *The scientific revolution: 1500-1800* (Boston: Beacon Press).

Hogben, L. (1940). *Science for the Citizen* (London: George Allen & Unwin).

Holton, G. & Brush, S. (2001). *Physics. The Human Adventure* (Piscataway: Rutgers University Press).

Kuhn, T. S. (1962). *The structure of scientific revolutions* (Chicago: Chicago University Press).

Lakatos, I. (1970). Falsification and the methodology of scientific research programmes. In I. Lakatos & A. Musgrave (eds) *Criticism and the growth of knowledge*, (Cambridge: Cambridge University Press), 91-196.

Mahoney, M. S. (1980). Christiaan Huygens: the measurement of time and of longitude at sea. In H. J. M. Bos et al (eds) *Studies on Christiaan Huygens* (Lisse: Swets & Zeitlinger), 234-270.

Maier, A. (1982). *On the threshold of exact science: collected essays* (Philadelphia: University of Pennsylvania Press).

Matthews, M. R. (1994). *Science teaching: the role of history and philosophy of science* (New York: Routledge).

Matthews, M. R. (2000). *Time for science education: how teaching the history and philosophy of pendulum motion can contribute to science literacy* (New York: Kluwer Academic Publishers).

Moody, E. A. (1951). Galileo and Avempace: the dynamics of the leaning tower experiment. *Journal of the History of Ideas*, 12, 163-193, 375-422.

Moody, E. A. (1966). Galileo and his precursors. In C. L. Golino (ed.) *Galileo Reappraised*, (Berkeley, CA: University of California Press), 23-43.

Olmsted, J. W. (1942). The Scientific Expedition of Jean Richer to Cayenne (1672-1673). *Isis*, 34, 117-128.

Porter, R. S. & Teich, M. (eds) (1992). *The scientific revolution in national perspective* (Cambridge: Cambridge University Press).

Randall, J. H. (1940). The School of Padua and the Emergence of Modern Science. *Journal of the History of Ideas*, 1, 177-206.

Wallace, W. A. (1981). *Prelude to Galileo: essays on medieval and sixteenth-century sources of Galileo's thought* (Dordrecht: Reidel Publishing Company).

Westfall, R. S. (1977). *The construction of modern science: mechanisms and mechanics* (Cambridge: Cambridge University Press).