Pendulum Motion: How the History and Philosophy of Science can Enrich Teaching and Promote Liberal Education

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Galileo in his final great work, *The Two New Sciences*, written during the period of house arrest after the trial that, for many, marked the beginning of the Modern Age, wrote:

> We come now to the other questions, relating to pendulums, a subject which may appear to many exceedingly arid, especially to those philosophers who are continually occupied with the more profound questions of nature. Nevertheless, the problem is one which I do not scorn. I am encouraged by the example of Aristotle whom I admire especially because he did not fail to discuss every subject which he thought in any degree worthy of consideration. (Galileo 1638/1954, pp.94-95)

To most students, and many secondary teachers, the pendulum does indeed seem to be an 'exceedingly arid' subject. It is frequently voted 'most boring' topic in physics; the looking at which does indeed bring on sleepiness. I will in this talk endeavour to show that with a little knowledge of the history of pendulum studies, and some awareness of the philosophical questions the studies raise, the teaching of pendulum motion can be made wonderfully engaging, and can shed much light upon the methodology of physics, the nature of science and the transformative role of science in culture and society.

The Pendulum in Western Science

The pendulum has played a significant role in the development of Western science, culture and society. The pendulum was studied by Galileo, Huygens, Newton, Hooke and all the leading figures of the Scientific Revolution. The pendulum was crucial for, among other things, establishing the collision laws, the conservation laws, the value of the acceleration due to gravity **g**, ascertaining the variation in **g** from equatorial to polar regions and hence discovering the oblate shape of the earth, and, perhaps most importantly, it provided the crucial evidence for Newton's synthesis of terrestrial and celestial mechanics.

The pendulum was important for the Galileo's new science, and it had a central place in Newton's physics, with the historian Richard Westfall remarking that 'without the pendulum, there would be no *Principia*' (Westfall 1990, p. 82). Subsequently the pendulum was at the core of classical mechanics as it developed through the eighteenth, nineteenth and early twentieth centuries, with the work of Stokes, Atwood and Eötvos being especially notable. Foucault's pendulum, as well as providing dynamical evidence for the rotation of the earth, also played a role in the popularisation of science in the late nineteenth and early twentieth centuries (Conlin 1999, Aczel 2003). Pendulum measurements enabled the shape of the earth to be determined, and were pivotal for the science of geodesy (Heiskanen and Vening Meinesz 1958).

Most importantly for Newton, the pendulum provided the crucial evidence for his synthesis of terrestrial and celestial mechanics. When Newton calculated the 'fall' of the moon in one second, and showed that it was precisely the portion of the fall of the pendulum predicted by his law of universal gravitation, he was able to demonstrate his claim that the heavens (moon and planets) obeyed the same laws as earthly bodies such as falling stones and projectiles. The heavens ceased to be a special realm of the Gods, or of essentially different substance from terrestrial material. The pendulum brought the heavens down to earth, so to speak.

Subsequently the pendulum was at the core of classical mechanics as it developed through the eighteenth, nineteenth and early twentieth centuries, with the work of Stokes (1851), Atwood and Eötvos being especially notable. The pendulum provided the first ever visible and dynamic 'proof' of the rotation of the earth. On February 2nd, 1851 Léon Foucault invited the French scientific community to 'to come see the Earth turn, tomorrow, from three to five, at Meridian Hall of the Paris Observatory' (Tobin 2003, Aczel 2003, 2005). His eponymously named long massive pendulum provided an experimental 'proof' of the Copernican theory; something that eluded Galileo, Newton and all the other mathematical and scientific luminaries who sought it.

Until Foucault's demonstration all astronomical observations could be fitted, with suitable adjustments such as those made by Tycho Brahe, to the stationary earth theory of the Christian tradition. The 'legitimacy' of such *ad hoc* adjustments in order to preserve the geocentric model of the solar system was exploited by the Catholic Church that kept the works of Copernicus and Galileo on the *Index of Prohibited Books* up until 1835 (Fantoli 1994, p.473). Mach of course disputed whether the rotation of Foucault's pendulum provided a proof, arguing that the rotation assumed a standpoint frame of reference, an argument repeated by some relativity theorists who maintained that absolute motion simply cannot be detected. But certainly to the lay person and to most 19th century physicists, the manifest rotation of Foucault's pendulum shown in the successive knocking down of markers placed in a circle, was a dramatic proof of the earth's rotation.

The simple pendulum, when displaced through a small amplitude ($<10^\circ$) oscillates with a natural frequency that depends solely upon its length. The pendulum manifests simple harmonic motion, whereby the restoring force on the bob (the tangential vector component of the pull of gravity) varies linearly with displacement. This is a marvellous physical system and is emblematic of a wide range of other such oscillating natural and perhaps social systems. The ideal, non-damped, simple pendulum is a conservative system in which the potential energy associated with the displacement is retained in the system when it swings. Galileo had an understanding of this, and demonstrated it so simply by showing how the pendulum, once released, retained its initial height, but did not exceed it. Low-level mathematical models can 'capture' the motion of simple pendulums. With more complicated pendulums – when the mass of the string, air disturbance, and fulcrum resistances are taken into account – more sophisticated mathematics and differential equations are required in order to 'capture' the behaviour. With double and triple pendulums chaotic motion can be induced which in turn requires still more sophisticated mathematics in order to be properly modeled. The whole pendulum system becomes more complex when the pendulum is driven by a varying torque at its point of suspension and the limits on its amplitude are removed. Then the pendulum's behaviour becomes more complex and consequently more resistant to mathematical capture. In recent decades mathematicians and physicists have jointly worked on this problem.[1]

The pendulum can support an extended and integrated pedagogical journey from elementary school to graduate programmes, in which the interplay of mathematics, technology, philosophy, culture, and experiment can be explored and appreciated. The dependence of science upon mathematics is beautifully illustrated at every stage of the pendulum story. The point can be made very early when students, through there own investigations, 'see' that period varies as length. With more sophisticated mathematical tools they can plot T against length (L) and, using simple curve fitting procedures, eventually see that if T is plotted against $\sqrt{(L)}$ a straight line is obtained. This leads to the mathematical relationship $T = k\sqrt{(L)}$. The square root of length is a mathematical construct rather than something commonly used in our everyday life and this exercise demonstrates the importance of mathematics in doing science.

The Pendulum and Timekeeping

The pendulum played more than a scientific role in the formation of the modern world. The pendulum was central to the horological revolution that was intimately tied to the scientific revolution. Huygens in 1673, following Galileo's epochal analysis of pendulum motion, utilised the pendulum in clockwork and so provided the world's first accurate measure of time (Yoder 1988). The accuracy of mechanical clocks went, in the space of a couple of decades, from plus or minus half-an-hour per day to a few seconds per day. This quantum increase in accuracy of timing enabled hitherto unimagined degrees of precision measurement in mechanics, navigation and astronomy. It ushered in the world of precision characteristic of the scientific revolution (Wise 1995). Time could then confidently be expressed as an independent variable in the investigation of nature.

Accurate time measurement was long seen as the solution to the problem of longitude determination which had vexed European maritime nations in their efforts to sail beyond Europe's shores. If an accurate and reliable clock was carried on voyages from London, Lisbon, Genoa, or any other port, then by comparing its time with local noon (as determined by noting the moment of an object's shortest shadow or, more precisely, by using optical instruments to determine when the sun passes the location's north-south meridian), the longitude of any place in the journey could be ascertained. As latitude could already be determined, this enabled the world to be mapped. In turn, this provided a firm base on which European trade and colonisation could proceed. The chances of being lost at sea were greatly decreased.

This story has been enormously popularised by Dava Sobel (1995). By utilising her work, and that of others, students can realize that the *chronological method* rather than the *astronomical method* was the most practical way to solve the problem of locating the longitude of a point on earth. Using Galileo's approach of correlating the occultation of the moons of Jupiter, the timing of a planetary transit, or the timing of a solar or lunar eclipse, were all beset with difficulties of observation and were generally unreliable. John Harrison's marine chronometer, which followed on his extensive pendulum clock constructions, solved the longitude problem. [2]

The clock transformed social life and customs: patterns of daily life could be 'liberated' from natural chronology (the seasonally varying rising and setting of the sun) and subjected to artificial chronology; labour could be regulated by clockwork and, because time duration could be measured, there could be debate and struggle about the length of the working day and the wages that were due to agricultural and urban workers; timetables for stage and later train and ship transport could be enacted; the starting time for religious and cultural events could be specified; punctuality could become a virtue; and so on. The transition from 'natural' to 'artificial' hours was of great social and psychological consequence: technology, a human creation, begins to govern its creator.[3]

The clock did duty in philosophy. It was a metaphor for the new mechanical worldview that was challenging the entrenched Aristotelian, organic and teleological, view of the world that has sustained so much of European intellectual and religious life. In theology, the clock was appealed to in the influential argument from design for God's existence – if the world functions regularly like a clock, as Newton and the Newtonians maintained, then there must be a cosmic clockmaker.[4]

Robert Boyle in rejecting the Aristotelian-scholastic view of the world being animated and moved by individual natures (or forms) that are part of the constitution of all things, wrote (in the same year that Newton's *Principia* was published) that:

> Whereas according to us, it is like a rare clock, such as may be that at Strasbourg, where all things are so skillfully contrived that the engine being once set a-moving, all things proceed according to the artificer's first design, and the motions of the little statues that as such hours perform these or those motions do not require (like those of puppets) the peculiar interposing of the artificer or any intelligent agent employed by him, but perform their functions on particular occasions by virtue of the general and primitive contrivance of the whole engine. (Boyle 1687/1996, p.13)

The Seconds Pendulum as a Universal Standard of Length

Huygens, in the process of elaborating his theory of pendulum motion and clockwork design argued in 1673 that the seconds pendulum could provide a new international standard of length (its length is effectively one modern metre). Undoubtedly this would have been a major contribution to simplifying the chaotic state of measurement existing in science and everyday life. He thought that this standard was dependent only upon the force of gravity, which he took to be constant all over the earth, and thus the length standard would not change with change of location. The standard was to be portable over space and time. Alas, Jean Richer's Cayenne voyage of 1672 suggested that the Paris seconds pendulum had to be very slightly shortened to beat seconds in tropical Cayenne (Matthews 2000, pp.144–146). Still, if a specific latitude were agreed upon (Paris? London? Berlin? Madrid?) then Huygens' proposal would answer to the pressing need of a natural, invariant length unit. Once a subsidiary volume standard was created, by filling this volume with rain water, an international mass unit would also be created. How Huygens' 1673 proposal of the seconds pendulum as a universal length standard was related to the century later (1793) decree of the French Revolutionary Assembly establishing the metre length standard as one 40th million part of the circumference of the earth, is an intriguing story with rich methodological, social and political overtones.[5]

Galileo's Methodological Revolution

The seventeenth century's analysis of pendulum motion is a particularly apt window through which to view the methodological heart of the scientific revolution. More particularly, the debate between the Aristotelian Guidobaldo del Monte (Galileo's own patron) and Galileo over the latter's pendular claims (period is independent of weight and amplitude, is isochronic and varies only as square root of length) represents, in microcosm, the larger methodological struggle between Aristotelianism and the new science. This struggle is about the legitimacy of idealisation in science, and the utilisation of mathematics in the construction and interpretation of experiments. Del Monte was a prominent mathematician, engineer and patron of Galileo (Renn et al. 2000, Matthews 2000, pp. 100–108). He kept indicating how the behaviour of pendulums contradicted Galileo's claims about them. Galileo kept maintaining that refined and ideal pendulums would behave according to his theory.

The heart of this debate is contained in Galileo's 1602 letter to del Monte (Drake 1978, pp.69-71). The letter illustrates in embryonic form the role of abstraction, idealisation and mathematics in Galileo's new science. Del Monte could not believe Galileo's pendular claims, and found them wanting when he rolled balls inside an iron hoop. He was a scientist-engineer, and enough of an Aristotelian, to believe that tests against experience were the ultimate adjudicator of claims in physics. Galileo's claims failed the test. But Galileo replies that *accidents* interfered with del Monte's test: his wheel rim was not perfectly circular and the rim was not smooth enough. These are perfectly understandable qualifications, yet it needs to be appreciated that they are *modern* qualifications. Galileo introduced this, now well established, process of abstracting from real circumstances to ideal ones.

The empirical problems were examples where the world did not 'correspond punctually' to the events demonstrated mathematically by Galileo. In his more candid moments, Galileo acknowledged that events do not always correspond to his theory; that the material world and his so-called 'world on paper', the theoretical world, did not correspond. Immediately after mathematically establishing his famous law of parabolic motion of projectiles, he remarks that:

> I grant that these conclusions proved in the abstract will be different when applied in the concrete and will be fallacious to this extent, that neither will the horizontal motion be uniform nor the natural acceleration be in the ratio assumed, nor the path of the projectile a parabola. (Galileo 1638/1954, p. 251)

One can imagine the reaction of del Monte and other hardworking Aristotelian natural philosophers and mechanicians when presented with such a qualification. When baldly stated, it confounded the basic Aristotelian and empiricist objective of science, namely to tell us about the world in which we live. Consider, for instance, the surprise of Giovanni Renieri, a gunner who attempted to apply Galileo's theory to his craft, who when he complained in 1647 to Torricelli that his guns did not behave according to Galileo's predictions, was told by Torricelli that 'his teacher spoke the language of geometry and was not bound by any empirical result' (Segre, 1991, p. 43).

Del Monte said that Galileo was a great mathematician, but a hopeless physicist. This is the methodological kernel of the scientific revolution. [6]

The development of pendular analyses by Huygens, and then Newton, beautifully illustrates the interplay between mathematics and experiment so characteristic of the emerging Galilean-Newtonian Paradigm. If students can be made familiar through their own investigations with some highlights of this nascent history of the pendulum, then they will have learnt something important about the origins and nature of modern science. It is acknowledged that science has moved on, and that it can be claimed that understanding seventeenth century debates about the pendulum is irrelevant to understanding modern techno-industrial science and its methodology.

This is a complex issue but, in brief, understanding origins, and development, is important for understanding and judging the present. This is true in just about all spheres – political, religious, social and personal – and no less so in conceptual matters.[7]

Further modern science has not so outgrown its methodological roots as to make irrelevant an examination of central seventeenth century epistemological debates. Even if it could be shown that modern science is methodologically different from its origins, nevertheless understanding where modern science has come from and, consequently, what occasioned the change, is still important. In education it is sensible to begin with simple or idealised cases. Presenting students with the full story – the truth, the whole truth, and nothing but the truth – is rarely a good idea. Concentrating on just some key aspects of a topic, be it in history, economics, biology, or what ever, makes pedagogical sense.

Galileo's debate with del Monte debate does capture in comprehensible form some of the core issues of epistemology – the distinction between observation and experiment, the relationship of evidence to knowledge claims, the role of theory in guiding experiment, and so on – and this gives an educational justification for its presentation. Provided students are made aware that the complete picture, or the modern picture, might be more complex, and provided they are encouraged to examine how science may have changed, then dealing with the seventeenth century is educationally and philosophically justified. These claims conform to the 'Genetic Method' in pedagogy; a method that consciously endeavours to have students re-tread the intellectual and experimental path that science has moved along from its origins.

The Pendulum and Piagetian Research

The pendulum entered into educational research and cognitive psychology with the publication in 1958 of the English translation of Bärbel Inhelder and Jean Piaget's *The Growth of Logical Thinking from Childhood to Adolescence* (Inhelder and Piaget 1958). Chapter Four of the book describes the pendulum tasks that Piaget and Inhelder gave to children to ascertain the extent to which they could isolate and manipulate potential variables (length, amplitude, weight, impetus) that affected the periodicity of the pendulum. The chapter is titled 'Operations of Exclusion of Variables' because only one of the four potential variables impact upon the duration of swing. Performing the task of isolating and uncoupling (controlling) the variables was seen as a window onto the child's cognitive structures or capacities and their developmental sequencing.

The tasks subsequently became a commonplace in diagnostic testing, being labelled 'Piagetian Reasoning Tasks' (PRT); as they involved extensive engagement with the child, the test procedure was called '*Méthode Clinique*' (or, the Clinical Method). Successful completion of the tasks was seen as indicative of the change from concrete to formal operational thinking. The subheadings of the chapter indicate the cognitive sequencing:

Stage I Indifferentiation between the subject's own actions and the motion of the pendulum.
Stage II Appearance of serial ordering and correspondence, but without separation of variables.
Stage IIIa Possible but not spontaneous separation of variables.

Stage IIIb The separation of variables and the exclusion of inoperant links.

The pendulum did for reasoning and formal thinking tests what it centuries earlier had done for timekeeping. Subsequently Piaget's cognitive theory, and his test protocols, have been extensively scrutinised.[8]

Enriched Scientific Literacy

Science literacy should be interpreted in a broad and generous sense, so that literacy is seen as involving an understanding and appreciation the nature of science, including its history, methodology and interrelations with culture. This is a demanding objective, but given the centrality of science to the development of society, culture and self-understanding, it is one that should be pursued by educationalists. In the USA, the *National Science Education Standards* (NRC 1996), and AAAS's reports *Project 2061* (Rutherford and Ahlgren 1990) and *The Liberal Art of Science* (AAAS 1990) all endorse this wider, liberal idea of scientific literacy.   They recognise that:

> Science courses should place science in its historical perspective. Liberally educated students – the science major and the non-major alike – should complete their science courses with an appreciation of science as part of an intellectual, social, and cultural tradition . . . . Science courses must convey these aspects of science by stressing its ethical, social, economic, and political dimensions. (AAAS 1990, p. 24)

This view is shared by the National Curriculum in the UK, a number of provincial science curricula in Canada, the Norwegian science curriculum, the Danish science curriculum, and the New South Wales state syllabus in Australia. Most science programmes aspire to having students know more than just a certain amount of science content, and having a certain level of competence in scientific method and scientific thinking. Most programmes want students to have some sense of the 'big picture' of science: its history, philosophy and relationship to social ideologies, institutions and practices (McComas and Olson 1998). In most countries, science education has dual goals: promoting learning *of* science, and also learning *about* science. Or, as it has been stated, science education has both *disciplinary* and *cultural* goals (Gauld 1977). Teaching the history and philosophy of pendulum motion is an ideal vehicle for realising some of these more ambitious aspirations for scientific literacy.

Teaching the Physics of the Pendulum and Its History[9]

The pendulum is a remarkably simple device and has long been part of the physics curriculum, a fact well documented in the IPP bibliography of pendulum articles that have appeared over the past fifty years in major science education journals (Gauld 2004). In its basic form – a string supporting a heavy bob – the pendulum demonstrates clearly the interchange between gravitational potential energy and kinetic energy and, with appropriate measuring instruments, the constancy of the total energy throughout its motion. Teachers have used the simple pendulum, swinging through small angles, to teach the skills of measurement and graphical techniques for deriving the relationship between dependent (in this case, period) and independent variables (length of the string).

More complex types of pendulums (such as the physical, spring-mass, torsional and Wilberforce pendulums) can be used to demonstrate dramatically a wide range of physical phenomena and provide a context in which students can become acquainted with the process of mathematical modeling. In the classroom pendulum motion provides a model for many everyday oscillatory phenomena such as walking and the movement of a child's swing. At the tertiary level there has been renewed interest in the pendulum to demonstrate chaotic behaviour. For these investigations the pendulum amplitude is unrestricted and the point of suspension is vibrated at varying amplitudes and frequencies. By removing the requirement that the amplitude be small the behavior of the pendulum as a non-linear oscillator can clearly be seen. The history of the uses of the pendulum in the study of kinematics and dynamics contains almost everything required to teach the fundamentals of kinematics and dynamics.[10]

The inclined plane and the pendulum were crucial in the development of Galileo's kinematics and Newton's dynamics in the seventeenth century. In many of the key problems of Galileo these simple devices were connected and used in creative ways to study motion, first without considering the forces involved (kinematics), and later investigate the forces that caused this motion (dynamics). Galileo 'diluted gravity' and extrapolated to free fall in an attempt to understand what Aristotle called 'natural motion'. Studying the pendulum, Galileo thought that an arc of a circle represented the 'least time' path of an object in a vertical plane.

Huygens went beyond Galileo and used the pendulum to find the expression for 'centrifugal' force on a body moving in a circle, as well as the modern formula for the period of a pendulum for small angles. He was the first to find the modern formula, namely that $T = 2\pi \sqrt{(L/g)}$ for the simple pendulum and also the first to write the mathematical statement for 'centrifugal' acceleration as $a = v2/R$. He used long and heavy pendula to determine the value of gravitational acceleration. He later correlated latitude and the local value of **g** to test his ideas. Huygens was also the first show (geometrically) that the path along which a pendulum would show isochronous motion was a cycloid and not the arc of a circle. From this background we can generate many experiments and problems that cover all those found in textbooks and beyond and in more interesting ways (Stinner and Metz 2003).

Huygens constructed the first pendulum clock that kept fairly accurate time. However, he failed to realize that the cycloid also represented the 'least time' path of descent of a particle in a vertical plane. It was left to Newton, Leibniz and Johannes Bernoulli to lay the foundation of a new branch of the calculus, in order to solve problems such as the brachistochrone, or 'least time' of descent between two points in a vertical plane. In the capable hands of Euler their approach then became a powerful method to solve minimum and maximum problems, called 'variational calculus'. Contemporary teachers can build a simple apparatus using two wires, one straight and the other roughly shaped as a cycloid, with two steel beads sliding down the wires. The bead travelling the longest path (the cycloid) takes the shortest time! This an example of a discrepant event that is sure to generate much discussion.

The work of Robert Hooke, a contemporary of Newton, should be included in this historical presentation. Textbooks mention Hooke only in connection with his law of springs, but Hooke has been called 'the British Leonardo'. He was a polymath: scientist, inventor and arguably the greatest experimenter of the seventeenth century. He was the curator of the Royal Society and sometime friend of Newton.[11] He used his law ($F = -kx$) to show that simple harmonic motion (SHM), like that of the pendulum, or an oscillating mass attached to a spring, arises when this law holds. His scientific battles with Newton were legendary. When Newton became the president of the Royal Society in 1705, he expunged all vestiges of Hooke from the Society.

We identify Robert Hooke by the famous drawing he made in his revolutionary *Micrographia* that he published at the age of 30 years. Discussing the confrontation between Newton and Hooke, students quickly come to realize that science is very much a human endeavor, and that scientists embody the full range of human foibles.

Students can be asked the question: ‘What experiments did Newton perform that suggested and confirmed his three laws of motion?’ Textbooks seldom discuss the experimental work of Newton beyond his optical experiments. It is not generally known that in his study of dynamics Newton used pendula to test his second and third laws of motion, as well as centripetal acceleration. Inertia, or his first law of motion, was seen as the consequence of a thought experiment that could not be tested directly. Newton went beyond Galileo’s idea of inertia as ‘the circumnavigation of an object on a perfectly smooth Earth’ to the idea of ‘straight line motion with a constant speed in deep space when there are no forces acting on the object’.

Newton’s second law, $F = ma$, can be applied to a pendulum to demonstrate that if Hooke’s law holds (restoring force is proportional to the displacement of the mass of the pendulum from the vertical) then we have simple harmonic motion. This part of the story is often told in textbooks, but Newton’s experiments to test his third law is seldom mentioned.

The third law, ‘action is equal to reaction’, was demonstrated by Newton using two long (3–4m) pendula and having them collide. He used a result of Galileo (that the speed of a pendulum at its lowest point is proportional to the chord of its arc) and applied it to the collision by comparing the quantities mass times chord length, before and after collision. This is one of the few detailed accounts found in the *Principia* that high school students can read and understand. Students soon see that the third law is really equivalent to the principle of the conservation of linear momentum (Gauld 1993, 1998, 1999).

Corollary III to his Laws of Motion states that ‘The quantity of motion, which is obtained by taking the sum of the motions directed towards the same parts, and the difference of those directed to contrary parts, suffers no change from the action of bodies among themselves’ (Newton 1729/1934, p.17). For Newton this concept of ‘quantity motion’ represents what we call momentum and this corollary states what we call the law of conservation of momentum (Cohen 2002).

Finally, Newton also used long bifilar pendula to test the equivalence of inertial and gravitational mass and came to the conclusion that to a ‘thousandth part of the whole’ they were equivalent. It is possible to replicate the experiments of Newton, using long pendula consisting of large wooden spheres, or bowling balls, suspended by wires.

The pendulum also played an important role in the next two centuries. Benjamin Robins in 1742 adapted the pendulum in his ballistic device to measure the muzzle velocity of bullets. Count Rumford, famous as the debunker of the caloric theory, in 1781 adapted Robins’ method and patented it. This method of finding the muzzle velocity of bullets was used until the recent effective application of high speed photography. Here we have an experiment that can be replicated using a ‘Gauss gun’ that propels ball bearings at low speeds.

Later, in 1790, George Atwood used the pendulum incorporated in his famous machine, named after him, as a research apparatus. One of the experiments he performed was to test

Newton’s second law of motion. Atwood’s machine is forever enshrined in physics textbooks problems, but it is seldom mentioned that Atwood’s approach was the first direct ‘test’ of Newton’s second law of motion. The pendulum in this experiment is part of the apparatus. A simple pulley can be used with two dissimilar weights and a pendulum to calculate the value of acceleration due to gravity.

In 1851 Jean Foucault designed a very long and heavy pendulum to demonstrate for the first time directly that the Earth revolves around its axis (Aczel 2003). Teachers can offer a good discussion of this dramatic and celebrated demonstration. Replication in the classroom is difficult but many science museums and centres have a Foucault pendulum demonstration.

Included in a rich history of the pendulum should be Hermann von Helmholtz’s studies of resonance. Although the original studies were made for sound, Helmholtz found an analogue for his colleagues Bunsen and Kirchhoff to explain the dark absorption lines of the solar spectrum. The important phenomenon of resonance can be dramatically demonstrated by using coupled pendula and, at the same time resonance demonstrations made using tuning forks imbedded in resonance boxes.

Teachers can discuss what may be the last of the great classical experiments to use a pendulum at the turn of the early twentieth century, namely the Eötvos experiment, to test the ratio of inertial and gravitational masses. This experiment is important even today and is connected with Einstein’s General Theory of Gravity and with a recent hypothesis of a ‘fifth force’ in nature.

Recently the pendulum has obtained a high profile in the demonstration of chaos theory. The study of the harmonic oscillator in all its manifestations in dynamics, electricity, and even atomic theory, can be traced back to the properties of the pendulum.

The Missed Curriculum Opportunity

The importance of history and philosophy for pendulum teaching can be gauged from looking at the recently adopted US National Science Education Standards (NRC 1996). The *Standards* adopt a liberal or expansive view of scientific literacy saying that it ‘includes understanding the nature of science, the scientific enterprise, and the role of science in society and personal life’ (NRC 1996, p. 21). The *Standards* also devote two pages to the pendulum (pp. 146–147): however there is no mention of the history, philosophy, or cultural impact of pendulum motion studies; there is no mention of the pendulum’s connection with timekeeping; no mention of the longitude problem; and in the suggested assessment exercise, the obvious opportunity to connect standards of length with standards of time, is not taken, rather students are asked to construct a pendulum that makes six swings in 15 seconds (Matthews 1998).

The *Standards* document was reviewed by tens of thousands of teachers and educators, and putatively represents current best practice in science education. It is clear that a little historical and philosophical knowledge about the pendulum could have transformed the treatment of the subject in the *Standards* and would have encouraged teachers to realise the expansive goals of the document through their treatment of the pendulum. This would have resulted in a much richer and more meaningful science education for US students. One can easily contrast the students’ experience of making a pendulum that swings six times in 15 seconds, with making one that swings ten times in 20 seconds, a second's pendulum. With the latter, they can measure that its length is one metre, and questions can be raised about whether this is an accident or if it is connected with the very definition of a metre. That this historical and philosophical knowledge is not manifest in the *Standards*, indicates the amount of work that needs to be done in having science educators become more familiar with the history and philosophy of the subject they teach.

The same point is recognised in the joint study undertaken by the Biological Sciences Curriculum Study and the Social Science Education Consortium when they say that the first barrier to school students understanding anything of the history and nature of science and technology is 'the preparation of teachers is inadequate' (Bybee et al. 1992, p. xiii). The problem is not confined to the US: it is an international problem.

The International Pendulum Project

The *International Pendulum Project* (IPP) had its origins with the publication of the book *Time for Science Education: How Teaching the History and Philosophy of Pendulum Motion can Contribute to Science Literacy* (Matthews 2000). This is a 13-chapter book with 1,200 references. It ranged widely over the history, methodology, cultural impact and pedagogy of pendulum studies. Interest in the subject matter of the book was sufficient to bring a large international group of scholars together for conferences at the University of New South Wales in 2002 and again in 2005. Participants saw the need to make teachers and students more aware of the important role played by the pendulum in the history of science and to investigate and promote better and more enriched pendulum teaching in schools.

Scholars from twenty countries contributed to the IPP, and their research appeared in three special issues of the journal *Science & Education* (vol.13 nos.4-5, 7-8, vol.15 no.6). Thirty-three papers have been published in the anthology *The Pendulum: Scientific, Historical, Philosophical and Educational Perspectives* (M.R. Matthews, C.F. Gauld & A. Stinner eds., Springer, 2005).

Liberal Education and Pendulum Teaching

The contextual, intellectualist, cross-disciplinary proposals advanced by the IPP find their natural home in the liberal education tradition, whose core commitment is that education is concerned with the development of a range of knowledge, a depth of understanding, and with the cultivation of intellectual and moral virtues. The intellectual virtues certainly include developing capacities for clear, logical and critical thought. These liberal goals are contrasted with goals such as professional training, job preparation, promotion of self-esteem, social engineering, entertainment, or countless other putative purposes of schooling that are enunciated by politicians and administrators.[12] The AAAS well states the liberal conviction when it says:

> Ideally, a liberal education produces persons who are open-minded and free of provincialism, dogma, preconception, and ideology; conscious of their opinions and judgments; reflective of their actions; and aware of their place in the social and natural worlds. (AAAS 1990, p. xi)

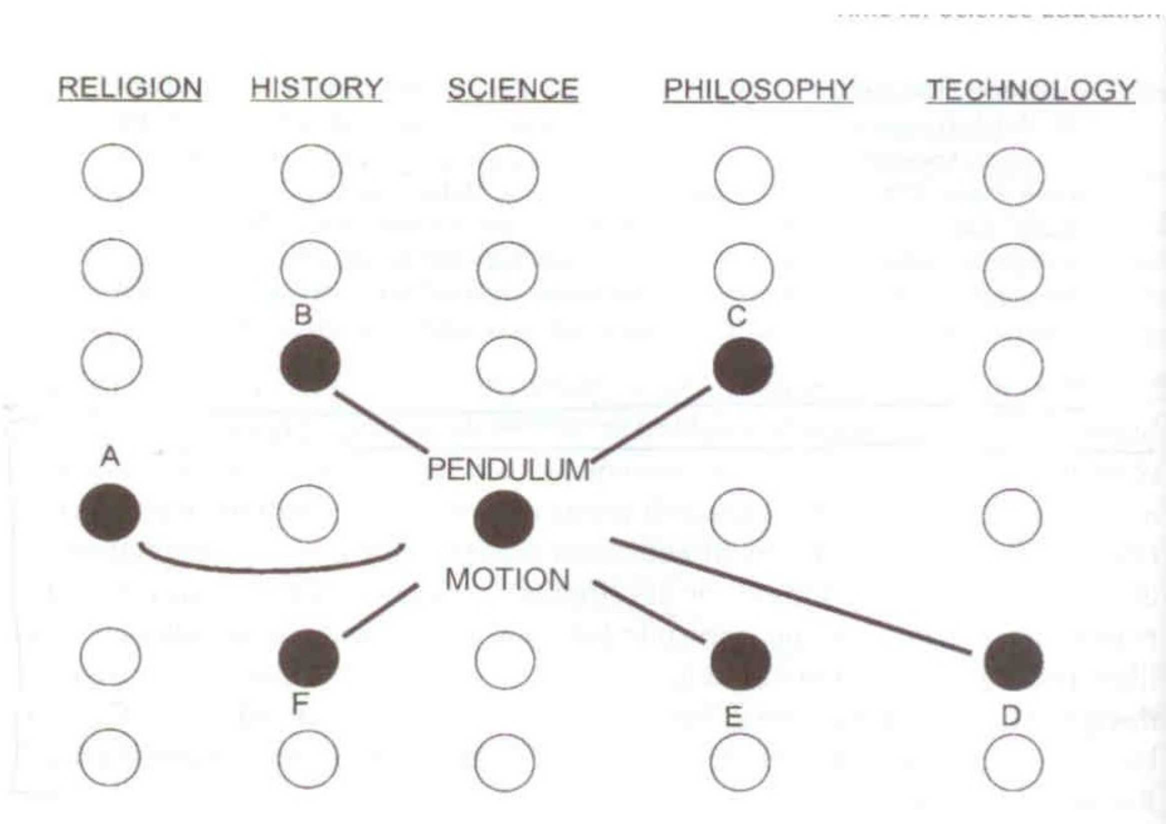
And then adds: 'The experience of learning science as a liberal art must be extended to all young people so that they can discover the sheer pleasure and intellectual satisfaction of understanding science' (ibid).

On this liberal view, science education is seen as contributing to the overall education of students, and thus considerations about aims and purposes of education constrain decisions about science education. The development of an educated person is the *telos* of school science teaching; this is the 'prize' that teachers' eyes need to be kept on.

The pendulum provides an accessible point of entry, or door, for students to learn important components of scientific knowledge, key features of the nature of science and of scientific method, and important aspects of the interplay between science and its social and cultural context. A good pendulum-based, or pendulum assisted, course allows students to learn:

(i) Basic scientific knowledge, such as the laws of fall, laws of motion, collision laws, and the laws of conservation of momentum and energy.
(ii) Essential features of scientific inquiry, such as observation, measurement, data collection, control of variables, experimentation, idealisation, and the use of various mathematical representations.
(iii) Important aspects of how science interrelates with society, culture and technology, as manifest in the use of the pendulum in timekeeping, navigation, length standards, and so on.

If the history and philosophy of science informs the teaching of pendulum motion then connections to other subjects in the school curriculum can easily be made. This can contribute to the integration, or at least coordination, of school subject matters. The following diagram represents such subject integration.



A The Design Argument **B** European Navigation	**C** Idealisation **D** Clock making	**E** Experimentation **F** Standardised Measures

Notes

[1] Many books deal with the physics of the pendulum. Specifically: Tavel (2002, pp. 219–231) deals with the progressive elaboration of the pendulum from simple to chaotic; Barger and Olsson (1973, pp. 63–75) work through the mathematics of Lagrangian formulations of pendulum motion; Rogers (1960), a text written for the PSSC Physics Course, has an excellent chapter on the pendulum; Pólya (1977) deals with Galileo's analysis (pp. 82–105) and gives an illuminating derivation of the central period/length equation (pp. 210–224).

[2] Dava Sobel has given the Longitude Problem enormous exposure (Sobel 1995). Other more detailed and wide-ranging treatments are in Andrewes (1998), Gould (1923) and Howse (1980).

[3] Many books deal with the social and cultural history of timekeeping, among them are: Cipolla (1967), Landes (1983), Macey (1980) and Rossum (1996).

[4] Macey 1980, Pt.II is a nice introduction to the utilisation of the clock in eighteenth century philosophy and theology. For a more general discussion of the rise of the Mechanical Worldview, see Dijksterhuis, E.J.: 1961/1986.

[5] Accounts of the development of the standard metre can be found in Alder (1995, 2002), Berriman (1953, chap. XI), Heilbron (1989), Kline (1988, chap. 9), and Kula (1986, chaps. 21–23). Some of the methodological and political story is told in Matthews (2000, pp.141–150).

[6] Some especially insightful discussions of Galileo's methodological revolution are McMullin (1978, 1990), Machamer (1998), and Mittelstrass (1972).

[7] Ernst Mayr, in the opening pages of his *The Growth of Biological Thought*, commends historical study to scientists in these terms:

> I feel that the study of the history of a field is the best way of acquiring an understanding of its concepts. Only by going over the hard way by which these concepts were worked out – by learning all the earlier wrong assumptions that had to be refuted one by one, in other words by learning all past mistakes – can one hope to acquire a really thorough and sound understanding. In science one learns not only by one's own mistakes but by the history of the mistakes of others.(Mayr 1982, p. 20)

[8] Some contributions are: Bond and Bunting (1995), Kuhn and Brannock (1977), Siegler, Liebert, and Liebert, (1973), Shayer and Adey (1981) and Sommerville (1974).

[9] This section is heavily dependent on the work of my IPP colleagues Art Stinner and Colin Gauld.

[10] For a more complete treatment of the use of the pendulum in physics programmes, see Stinner and Metz (2003).

[11] For the life and achievements of Hooke see Drake (1996), Jardine (2003) and contributions to Hunter and Schaffer (1989).

[12] Some of the more prominent advocates of liberal education have been: Mortimer Adler (Adler 1939/1988), G.H. Bantock (Bantock 1981), Paul Hirst (Hirst 1974), Richard McKeon (McKeon 1994), John Henry Newman (Tristram 1952), Richard Peters (Peters 1966) and Israel Scheffler (Scheffler 1973). See Kimball (1986), also contributions to Orrill (1995), and to Schneider and Shoenberg (1998). Elliot Eisner, in his review of curriculum ideologies, calls this educational tradition ‘rational humanism’ (Eisner 1992). There are connections with the Germanic educational idea of *Bildung* (Bauer 2003).

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