THE PENDULUM

The Pendulum

Scientific, Historical, Philosophical and Educational Perspectives

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Table of Contents

Philosophical Perspectives

Educational Perspectives

The Pendulum: Its Place in Science, Culture and Pedagogy

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Abstract. The study and utilisation of pendulum motion has had immense scientific, cultural, horological, philosophical, and educational impact. The International Pendulum Project (IPP) is a collaborative research effort examining this impact, and demonstrating how historical studies of pendulum motion can assist teachers to improve science education by developing enriched curricular material, and by showing connections between pendulum studies and other parts of the school programme especially mathematics, social studies and music. The Project involves about forty researchers in sixteen countries plus a large number of participating school teachers.[1] The pendulum is a universal topic in university mechanics courses, high school science subjects, and elementary school programmes, thus an enriched approach to its study can result in deepened science literacy across the whole educational spectrum. Such literacy will be manifest in a better appreciation of the part played by science in the development of society and culture.

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 seventeenth-century science. 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

M.R. Matthews et al. (eds.), The Pendulum, 1–17.

earth to be determined, and were pivotal for the science of geodesy (Heiskanen and Vening Meinesz 1958).

The simple pendulum, when displaced through a small amplitude ($<10°$) 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 modelled. 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.[2]

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.[3]

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.[4]

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.[5]

Horology

The link between the seventeenth century revolution in timekeeping, and developments in physics and methodology is oft-ignored. Despite there being scores of excellent books, and hundreds of research articles, on the technical, social and comparative history of timekeeping, there are few studies that connect the pendulum clock to Galileo and Huygens' discoveries of the physics of the pendulum, and even less studies that connect the pendulum clock to the Galilean revolution in scientific methodology. Galileo's law of isochronous motion, and hence his directions for using the pendulum in timekeeping, could not be accepted until he threw off the straight- jacket placed on science by the epistemological primacy given by Aristotelians to experience and the evidence of the senses. As long as scientific claims were judged by what could be seen, and as long as mathematics and physics were kept separate, then Galileo's pendulum claims could not be substantiated. Their substantiation required not just a new science, but a new way of judging scientific claims, a new methodology of science.

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.[6]

Philosophy of Science and Pendulum Studies

Philosophy of science should be informed by history of science. This is one of the important contributions of Thomas Kuhn's legacy to science studies. Historical study of the pendulum case shows how Galileo initiated the methodological transition which was to culminate in the Galilean-Newtonian Paradigm (GNP) which quickly came to characterise the Scientific Revolution, and the subsequent centuries of modern science. The Aristotelian epistemological taboo on manipulating nature, or experimenting, was lifted, as was the Aristotelian hesitancy to mix mathematics with science. The long entrenched conviction that only undisturbed or 'natural' states-of- affairs would reveal their essence was slowly replaced by the view that nature has to be simplified, that variables had to be controlled, that 'inputs' and 'outputs' needed to be measured and represented mathematically, and that scientific understanding was something other than grasping the essence or nature of things and ascertaining their final causes or teleological purposes.[7]

There are, admittedly, problems with 'historicised' philosophy of science. One is that history can be mined merely to find support for antecedently arrived at epistemological positions. History is then 'reconstructed' to suit whatever philosophical position is being advocated. Albert Schweitzer, in his monumental 1910 work on *The Quest of the Historical Jesus* that traced the history of Christian interpretation of Jesus, remarked that 'each successive epoch of theology found its own thoughts in Jesus .... But it was not only each epoch that found its reflection in Jesus; each individual created Him in accordance with his own character' (Schweitzer 1910, p. 4). Schweitzer could equally have been talking of Galileo. It is notorious that Galileo has been made out to be a shining example of the full range of epistemological positions: from rationalist, through empiricist and experimentalist, to positivist, and to methodological anarchist (Crombie 1981). The common thread is that the epistemology attributed to Galileo is usually the one favoured by the biographer or interpreter.

There is a chicken-and-egg problem with the Kuhnian stance. If philosophy of science emerges from history of science, how is the history first demarcated? Independently of a philosophical, normative, position what will count as the subject matter of history from which our methodological lesson is to be drawn? Do we draw lessons equally from Christian Science, National Socialist Science, Lysenkoism, Astrological Science, Islamic Science, Hindu Science, New-Age Science as well as classical mechanics, thermodynamics, and quantum mechanics?

The two standard ways around these problems are essentialist approaches on the one hand, and nominalist approaches on the other. For essentialists, history is ignored and science is characterised on *a priori* grounds – usually philosophical, political or sometimes religious. For nominalists, philosophy is ignored, and science is taken to be whatever people claiming to do science actually do. This option is popular among cultural historians of science and sociologists of science. It is better to steer a path between these two alternatives by focussing on an episode that all can agree upon as being good science, and then teasing out some methodological lessons from that. If the achievements of Galileo and Newton are not considered good, or at least, representative, science, then the very question of the epistemology of science loses its cogency. This is a version of the common 'paradigm case' argument in philosophy: to understand something, first find an exemplary instance of it, and examine its features and ramifications.[8]

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 and Galileo over the latter's pendular claims, 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. Del Monte said that Galileo was a great mathematician, but a hopeless physicist. This is the methodological kernel of the scientific revolution. 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.[9] 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.

'Big Picture' History of Science

The pendulum story fits into the 'big picture' or 'grand narrative' genre of history of science: it deals with the interrelatedness of timekeeping, pendulum science, philosophy and social forces; and it endeavours to draw methodological lessons from all this. Big Pictures in the history of science need not be painted with broad brush strokes. The IPP endeavours to compose a big picture but does so with fairly fine brushes. The IPP deals with both *internal* matters concerning the development and refinement of scientific concepts; and *external* matters such as the social and cultural contexts in which science develops. This distinction needs detailed attention, and ultimately it is somewhat conventional. For instance, a change in epistemology was fundamental to Galileo's achievements in understanding pendulum motion. Is then epistemology internal or external to science? Huygens' recognition of the isochronous nature of cycloidal motion rested upon the new geometrical analysis of the cycloid curve. Is then mathematics internal or external to science? Neither Galileo's nor Huygens' proposals for utilising the pendulum in timekeeping could be experimentally tested until technological advances in metallurgy, gear-cutting and escapement design were made. Is then technology internal or external to science? Once science is recognised as part of the intellectual culture of a society then the separation of 'internal' and 'external' elements borders on being conventional.

That the distinction is blurred, does not mean that it cannot be made in some form. It is clear that the longitude problem played a major role in the development of clockwork. Solving longitude was one of the major preoccupations of European nations from the fifteenth to the eighteenth centuries. King's ransoms were offered for its solution. Despite all the external financial and political pressure, a solution had to wait on scientific, methodological and mathematical progress. The world was the judge of putative solutions, not political or ideological interests. This is an important point to be appreciated at a time when many maintain that science simply dances to the tune of the last patron who paid the fiddler. In science, paying the fiddler and getting a good dance, are two different things.

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.[10] Contributors to the IPP appraise this research tradition, commenting on its strengths, weaknesses and seeing how pendulum investigations might still be used to assess higher order mental capacities and children's ability to reason proportionally, to control variables, to make inferences, to draw conclusions about the truth of hypotheses given certain evidence – in brief, to think scientifically.

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

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 modelling. 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 behaviour 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. The following is a brief history of the pendulum and a list of suggestions for the physics classroom.[11] Clearly, teachers who would use a historical approach like this one must have more than a cursory acquaintance with the history of science.

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 $a = v^2/R$. 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. 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.[12] 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'. His 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.

Curriculum Considerations

The educational usefulness of the IPP 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. 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. Hopefully the research publications and classroom materials generated by the IPP will do something to ameliorate this problem.

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 and a depth of understanding, and with the cultivation of intellectual and moral virtues.[13] 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. The AAAS well states the matter 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.

Participants in the IPP believe that the pendulum provides an accessible point of entry, or door, for students to learn important components of scientific knowledge, key features 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.

Further, the same door is available at all stages of a student's education, from elementary school to graduate studies in physics. What is 'behind the door' will change with teacher sophistication, student preparedness and curricular demands. It is hoped that the IPP research publications appearing in two special issues of *Science & Education* (Vol. 13, Nos. 4–5, 7–8), an associated anthology (Matthews, Gauld and Stinner 2005), and the pedagogical materials that will follow, will assist teachers to convey this richer view of science to students, and consequently deepen students appreciation of science and its impact on human thought and well being.

Notes

[1] The Project is coordinated by Michael Matthews at the University of New South Wales. The book *Time for Science Education: How Teaching the History and Philosophy of Pendulum Motion can Contribute to Science* Literacy (Matthews 2000) provides an overview of some of the scholarly and pedagogical matters with which the Project is concerned. IPP details can be seen at www.arts.unsw.edu.au/pendulum/ .

[2] 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).

[3] 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).

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

[5] Macey 1980, Pt.II is a nice introduction to the utilisation of the clock in eighteenth century philosophy and theology.

[6] 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).

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