Early modern scientific and technical activities: sorting out “science” and “technology”.

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ABSTRACT

This paper is concerned with the nature of scientific and technical work, particularly in the early modern period. The background to the work is outlined, and an attempt made to obtain a workable definition of the terms employed, by means of some outline examples from the period. A more detailed study is then made of the development of mechanical clocks, and particularly the place of scientific work in it. This brings out rather different ideas from those presently accepted, which bear upon how we think about the antecedents of modern science and technology.

TECHNOLOGY, AND EARLY MODERN SCIENCE.

Science and technology, and their relationship, have been a subject of discussion in the literature for over thirty years[1]. Much of this discussion has covered modern science and technology, and has exposed issues of status, of the perceptions of practitioners, and the complex interplay of activities involved[2]. An important motive sustaining this discussion has been to establish the intellectual credentials of technology. Recently the discussion has been extended to include consideration of the antecedents of modern

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[1] Edwin Layton, in “Technology as knowledge”, *Technology and Culture*, 1974, 15: 31-41 took exception to the omission of knowledge from the definition of technology given by Charles Singer, E. J. Holmyard and A. R. Hall in “*A history of technology*”, (London, 1954-8).

[2] Edwin Layton, “American ideologies of science and engineering”, *Technology and Culture*, 1976, 17: 68-701; Barry Barnes, “The science-technology relationship: a model and a query”, *Social Studies of Science*, 1982, 12: 166-172; Ronald Kline, “Construing technology as applied science”, *Isis*, 1995, 86: 194-221.

practice, whether they lie in early modern science, or elsewhere[3]. This paper concerns the relationship between early modern science, and technology, and how we think about them.

A continuing problem in thinking about the relationship between science and technology is that the scope of science is ill defined. For example, to describe technical knowledge as "knowing how to…", and to attribute unqualified "knowing" to science[4], apart from being an unrealistic limitation on technology, perhaps more importantly implies that scientific knowledge can include technical knowledge. This impression, that scientists can understand technology, but not vice versa, is widely conveyed elsewhere in the literature[5]. The same literature also makes careful distinctions to define what is scientific, and separate it from technology[6]. Science, in these terms, is somehow both exclusive and yet unrestricted in its scope.

To try to establish better definition of science, let us consider the example of projectile motion and of the pendulum, both of which were part of the development of early modern science. Let us also restrict scientific knowledge to "knowing in theory that...", a restriction that is in agreement with previous criteria for distinguishing the scientific. Scientific knowledge tells us that projectile motion follows a parabolic path, in a theory which describes it as motion under gravity alone, i.e. under a uniform unidirectional acceleration. It does not say what the path will be in a real ballistic problem, nor how to hit a target, nor, least of all, how to make a machine to achieve that end. A scientific study of the effect of air resistance, which is significant in ballistics, is not dedicated to

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[3] Peter Dear, "What is the history of science the history of?", *Isis*, 2005, 96: 390-406.

[4] A.R. Hall, "On knowing, and knowing how to…", *History of Technology*, 1978, 3: 91-103.

[5] See H Floris Cohen, *The scientific revolution : a historiographical inquiry* (Chicago: University of Chicago Press, 1994).

[6] Cohen, *The scientific revolution*, p. 346 .

more accurate targeting, or increased range, but instead studies the phenomenon in whatever context gives the most fundamental insight into it. For the pendulum, scientific knowledge tells us that it swings with a periodic time determined by its length, according to a theory that assumes a small angle of swing, taking place under gravity alone. It does not say how to operate a pendulum to measure time accurately, nor how to construct a machine to do so automatically. A scientific study of the effect of larger amplitude of swing would attempt an exact analysis of how it affected the period, either using techniques from another part of scientific knowledge, or by developing new techniques, which might then be more widely applied. It would not be concerned with whether the effect was important in practice, or how to circumvent it.

Having clarified the role of science in this way, the large extent of the activities that fall outside science becomes more apparent. For example, deriving the simple pendulum formula from the theoretical model described above is scientific, as is an experiment to validate it. If an operator obtains a pendulum for timing purposes with a desired period by calculating the length required according to the formula and constructs it thus, that is science in the service of technology. If the pendulum is then used for astronomical observation, that is technology in the service of science. If the operator instead obtains the period by adjusting the length using systematic experiment, that is not a scientific procedure, but a technical one. If the operator, seeking a reliable time measurement, compares similar pendula with different amplitudes of swing, observes that the larger amplitude has a longer period, and attempts to estimate the magnitude of that effect by observation, that is also a technical activity, not scientific.

Another problem in thinking about science and technology is that the terms “science” and “scientific” are used to refer to intellectual qualities such as completeness, rigor, and generality. For example, to convey the intellectual depth of modern developments in engineering theory Edwin Layton described them as “increasingly scientific, in some sense”[7]. With the definition discussed above, we should describe them instead as “increasingly technical”. This change in terminology retains the sense of the original, in that it contrasts the mechanical, analytic and measured aspects of these developments with the non technical aspects of engineering design, such as the experiential, aesthetic, cultural and ethical ones.

With this idea of technical activity in mind, we can look at the characteristics that have been held to distinguish early science from it, and see how they work in less hypothetical instances. These characteristics can be summarised as: Science established fundamental principles with general validity, rather than finding *ad hoc* solutions to particular problems using rules of thumb. It carried through elaborate mathematical proofs which required sound principles and rigorous analysis to succeed. It broke out of the common sense or intuition that limited technical thinking. Science replaced the speculative trials of available alternatives that were used by artisans by planned experiments that could validate well defined theories with precision.

The clarity of these distinctions is easily overstated, for example in experimentation. It would be implausible to suppose that renaissance industry could have developed processes for the consistent, routine production of uniform, robust glass tubing, or of brass strip and rod suitable for precision clocks, without conducting systematic experiments, keeping records, and analysing them rationally. We would expect that the Venetian Arsenal did, like any production environment[8], move heavy, round items from place to place by rolling them down slopes, and also dealt with the problem of controlling their gathering momentum. There is no reason to suppose that the

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[7] Edwin Layton, “Through the looking glass; or, News from Lake Mirror Image”, *Technology and Culture,* 1987, 28:594-607 p. 603.

[8] see for example http://www.spectrasystems.co.uk/roller_track.htm

experimentation involved in this was extended beyond investigating the problem in hand, but it does demonstrate the closeness of Galileo's famous investigation of motion on an inclined plane to an entirely technical activity within his experience.

Inertia is an often quoted example of a rigorous and counter intuitive scientific principle, since contemporary experience was of mechanical systems with high levels of friction, which made it natural to assume that all motion must decay. The degree to which it is counter intuitive can also be overestimated: sustained uniform motion was well within immediate human experience. A particularly forceful manifestation of it is undergone by a boatman attempting to manoeuvre a laden barge on still water. This kind of experience has been available since classical times, but renaissance technology made it far more common. An indication of the contemporary state of mind can be obtained from a work on mechanics: Benedetti, when he justifies his assertion that a rotating wheel will always come to rest[9], appeals only to mechanical causes of decay, and does not appear to think that a natural decay in impetus will be expected by his readership. In the context of the changing material conditions of life in the period, and of the degree of refinement and complexity achieved by renaissance industry being far in advance of previous experience, we must allow for changes in intuitive or commonsense attitudes when assessing the distance between them and the scientific principle when it is proposed.

The rigour required for successful calculations is again a matter of degree: Benedetti considered that motion in a circle must decay, not only due to friction, but also because it is constrained from the natural rectilinear path. He did not achieve the clarity of decomposing the tangential and the radial effects, or of seeing that the former might not

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[9] *Speculationum*, 1585, Trans. Stillman Drake and I. E. Drabkin, in *Mechanics in sixteenth-century Italy* (Madison: University of Wisconsin Press, 1969) p. 186.

be affected by the latter. Galileo managed to decompose the horizontal and vertical components of projectile motion, but did not unify his treatment of them[10]. Huygens, in analysing pendulum motion, thought in terms of effective weight[11], rather than of the effect of weight. We see that when principles emerge, they do so progressively; at each stage, useful calculations are being done with the current level of insight, and with various degrees of rigour.

When more complex technical systems are involved, the relationship between principle and rule of thumb becomes even more complicated. Beekman's early insights into the mechanism whereby a vacuum may not exist[12] are those of an artisan, familiar with hydraulics[13], encountering a philosophical doctrine incompatible with his experience. The failure of Baliani's attempt to construct a high siphon[14], and the insights he derived from it, defined the technical context of Berti's experiment with a water column, which, despite its systematic thoroughness, did not convince those who had their minds made up about the vacuum. Viviani's mercury column experiment is remembered for Torricelli's cogent argument based upon it, that is, for its eventual impact on doctrine[15]. Pascal's experiments with tall water columns had a similar doctrinal goal[16], and extended the engagement of the investigation in the wider natural world. Boyle's

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[10] Alexandre Koyre, *Metaphysics and Measurement* (Chapmand and Hall, London), 1968, Ch III.

[11] Joella Yoder, *Unrolling time: Christiaan Huygens and the mathematicisation of nature* (Cambridge, 1988), p. 23.

[12] W. Knowles Middleton, "The place of Torricelli in the history of the barometer", *Isis*, 1963, 54:11-28, p. 12

[13] see http://galileo.rice.edu/Catalog/NewFiles/beeckman.html

[14] W. Knowles Middleton, "the history of the barometer", p. 13

[15] W. Knowles Middleton, "the history of the barometer", p. 19; Cohen, *The scientific revolution,* p. 347 and Gribbin, *Science a history* (London: Penguin, 2003) p. 115.

[16] Koyre, *Metaphysics and Measurement,* p. 148

experiment with the lift pump on a high column of water[17] focuses on a particular technical system, in a practical situation. It examines a familiar property of the pump, that the lift is limited to about 10m, and constructs and operates the pump so as to define this limit. It includes careful observation to confirm that principles previously demonstrated on specialist apparatus in the laboratory were governing the performance of the artefact in practice. It is one of many examples of technical science of the period, in which an artefact or process is investigated systematically. The technical quality of such activities has been assessed as very low in some earlier historical studies[18], a finding that would support a clear distinction between science and technology[19]. More recent analysis has shown the technical quality of the historical studies themselves to be inadequate, and of the work studied to be rather superior,[20] undermining that clarity.

From a technical point of view, the progress of this early work on air pressure is fairly straightforward. In the everyday experience prior to the renaissance, air is not greatly compressed or rarefied, so it behaves like a liquid, and a vacuum is out of the question. The technology for a lift pump is elaborate: it requires valves and seals, pipes, taps and fittings that are air tight. To operate at high lifts, this system has to be robust and carefully made, something which would be very rare before renaissance technology. To develop and use the system you have to deal with the endless extensibility of air, and encounter the consequent limitation that its pressure cannot deviate more than a certain

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[17] Steven Shapin, *The scientific revolution* (Chicago: University of Chicago Press, 1994), p. 39.

[18] Richard S. Westfall, ‘Robert Hooke, mechanical technology and scientific investigation’, in John G. Burke, (ed.), *The Uses of Science in the Age of Newton* (Berkeley: University of California Press, 1983), pp. 85–110.

[19] Cohen, *The scientific revolution*, p. 194

[20] S H Joseph, “Assessment of the scientific value of Hooke’s work”, in *Robert Hooke: Tercentennial Studies*, Michael Cooper and Michael Hunter, eds. (London: Ashgate, 2006), pp. 89-110.

amount below normal. You do not need to visualise yourself as immersed in a sea of air, nor to assert the possibility of the void, to master its design and operation, but there is obviously more happening in the system than a natural *horor vacui*. From a scientific point of view, the encounter with the principle of the vacuum is central, but unsatisfactory. The outcome of experiments with water and mercury columns depends on the air contained in them[21]. They could be indefinitely extending a continuum of air, and, indeed, since they produce spaces that are not void, cannot demonstrate its existence. The technical and scientific approaches find a union in the experiments and calculations of Boyle and Hooke which demonstrate the power of locating an absolute zero of air pressure and of observing an ambient atmospheric pressure, in describing both the operation of the pump and the natural world. The void is no longer under consideration, instead that condition is a point on a diagram defining a property of a material, the use of which is well understood.

It seems, from the above examples, that early modern science is not clearly distinguished from technology by the absolute properties of the activities, or ways of thinking, that it employs. Science does have a greater concern for principles, but most distinctively in that it inherits them, and is exercised by the prospect of changing them. The philosophical and cultural aspects of this concern have been very well studied in terms of what is known[22]. For the relationship between science and technology, the key aspect of this concern is for the formation and delivery of doctrine. Thinking in terms of doctrine, rather than knowledge, is useful in some ways: It brings into view the

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[21] A. E. Bell, *Christian Huygens* (London: Edward Arnold, 1947), p. 48, Koyre, *Metaphysics and Measurement*, p. 150

[22] Shapin, *The scientific revolution*, John Pickstone, *Ways of knowing* (Manchester: University Press, 2000), and these authors and co-workers elsewhere.

education of practitioners of technology as well as science, and of their history, and it avoids philosophical anxieties about the nature of knowledge.

The foregoing examples are too brief to be more than indicative of the relationship between scientific and technical activities. In the following section a study is made in somewhat more detail of aspects of the development of mechanical clocks. Early clocks, from about 1300 onwards, were governed by a beam or wheel oscillating about its centre, driven to and fro by an escapement mechanism, powered by a weight, rather like a modern balance wheel watch, but with no hairspring. The pendulum clock of Huygens introduced a new mechanical principle in 1656, because the motion of his pendulum was dominated by gravity, which gave it a natural period of oscillation, around which the clock was designed. Subsequently, many early clocks were converted to pendulum operation. Huygens' analysis of pendulum motion established in theory the independence of period on amplitude of motion in a cycloidal path and the means for obtaining such a path in an embodiment. In order to do so he advanced the state of the art of the analysis of the rectification of curves[23]. This history, in which a centuries old conventional mechanism is revolutionised, by the advent of an early scientist who applied an advanced mathematical analysis to the problem, is considered a clear example of the distinctively different qualities of science and technology[24], and of the impact of science on technology[25].

MECHANICAL CLOCKS

The earliest development of mechanical clocks remains obscure, but some technical appreciation of it is possible, by considering the artefacts that resulted. Constructors of

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[23] Yoder, *Unrolling time* is dedicated to these mathematical developments.

[24] Cohen, *The scientific revolution*, p. 353.

[25] Alexander Keller, "Has science created technology", *Minerva*, 1984, 22: 160-182, p. 164.

mechanical clocks were, according to one report, trying to make a wheel that would rotate once per day[26]. Such a slow motion is hard to keep steady and uniform, but a faster one can be, by, for example, an air resistance based governor, such as was used to control the speed of the striking system of early clocks. The contemporary technology of gear trains could provide a slow enough motion if the fast end of the train were regulated by some sort of governor. The motion can also be sustained for long enough to make a useful clock if it is driven by a falling weight attached to the slow end of the gear train. This mechanism is impractical for a timekeeper, because the drive train would have to be of so high a ratio that, for a drive train that could be constructed with contemporary technology, friction would reduce the drive by a large and variable fraction, and perhaps to zero. The bearings of a governor would also wear out rapidly. A slower, but regular, motion was needed: this is provided by a foliot, a horizontal beam with equal weights hung near each end, suspended from a cord at its mid point, so that it can swing about the cord as axis. This motion is amongst the slowest and steadiest that might be observed in the course of operating early machinery, for example in lifting and positioning: it is much slower than the side to side swinging of a weight that forms a pendulum. The cord suspension of the foliot reduces friction, and the weights add momentum, so that the motion requires little power to be sustained, and so the drive weights can then be of feasible size. Manual experiments with a foliot arrangement could demonstrate the feasibility of sustaining a regular motion by applying the drive force in alternating directions. This process can be directly imitated by spoked wheels, working like the strob arrangement that was occasionally used in later clock construction[27]. The development into a verge and crown wheel arrangement would

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[26] Lynn Thorndike, “Invention of the mechanical clock about 1271 AD”, *Speculum*, 1941, 16: 242-243, p. 242.

[27] David Landes, *Revolution in Time* (Harvard University Press, 1983), fig5.

require considerable ingenuity, but can be seen as an variation on the same principle evolved through economy and manufacturing considerations. The preceding account is speculative, but does provide an insight into the conditions that early clockmakers encountered, and helps set the context for further development.

Even with the use of the slowly oscillating foliot, the technical requirement, of high reliability and continuous duty, for a working clock was severe. To construct one involved specialist knowledge in sourcing valuable materials and working them to the necessary precision, and substantial finance[28]. Maintenance and regulation were required from a clockmaker for the life of the clock, which might extend over several decades. Worn parts could be replaced, but frequent replacement would represent a severe disadvantage due to the expense. The foliot regulator, or its balance wheel equivalent in smaller clocks, became so standard that even as early as 1380 it could be taken for granted in the description of a clock[29]. Domestic size clocks were made by 1440, and springs employed instead of weights so that the mechanism became portable: in 1477 a variety of clocks, alarm, striking, spring and weight driven, were catalogued[30]. By 1500 they were small enough to be carried on the person as a watch. Spring drive implies an even more stringent need for low friction, because of the limited energy stored; springs also require refined processing to achieve usable composition, uniformity of thickness and temper.

As with other industrial developments, the availability and working of materials was crucial. Early clocks were made of iron, with critical small components in steel.

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[28] Otto Mayr, *Authority, liberty and automatic machinery in early europe* (Johns Hopkins University Press), 1986, p. 7

[29] H Alan Lloyd, *Some outstanding clocks over seven hundred years 1250-1950* (London: Leonard Hill), p11.

[30] Lloyd, *Some outstanding clocks*, p 33.

Construction of the frame followed carpentry principles, with each part purpose made, and fixed with wedges; screws were not employed until about 1500[31]. Carbon steel tools were used to make journal holes, and hand held on the lathe to turn arbors, at speeds slow enough not to distemper the tool[32]. For large clocks, spur gears were roughly shaped using blacksmithing methods, and finished by filing against a pattern. Lantern pinions, which could be made without the difficult shaping of a deep section, were common. Of particular importance in the availability and quality of materials was the spread of blast furnace production of pig iron, and the development of the cementation process for steel, which meant that steel could come from other than a few natural sources.

The manufacture of an early clock was far from routine, and the outcome unpredictable. The work was slow, and relied on high manual skills to have even a chance of success. Reduction in size is essential for development of alternative mechanisms: in the period when each machine is a substantial project, experimentation and the cost of failure is prohibitive. The foliot mechanism itself underwent development, with the introduction of hog's bristle limiters[33] around 1500 to define the amplitude of the foliot swing, and improve the regulation. A bristle was set at the extreme of the motion so that the foliot bounced off it at the end of each swing. The bristles were set close to the axis, so they provided a substantial elastic element in the return. This development invites comparison with the introduction of the balance spring, giving a natural period to the swing, in the seventeenth century; the limiters were not developed towards obtaining a

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[31] Lloyd, *Some outstanding clocks*, p 30.

[32] P.T. Craddock and M.L. Wayman, "The development of european ferrous metallurgy", in *The ferrous metallurgy of early clocks and watches*, British Museum Occasional Papers Number 36, ed Michael Wayman (London, 2000), pp13-28.

[33] Lloyd, *Some outstanding clocks*, p. 35

natural period, so there is no evolutionary path, but the presence of a spring element in exactly the right place in the mechanism has to be suggestive to anyone familiar with the technology.

With the wider availability of better tools and cheaper materials, and sufficient sufficiently wealthy customers, clockmaking could become a viable trade: clockmakers' companies were set up in the period 1544 to 1630. Perhaps the most significant change in the manufacture of precision clocks came in the 1560s, with the introduction of brass in a workable and hardwearing form[34]. This meant finer, faster work, and reduced friction and wear by using steel on brass for gears and bearings. These factors produced a drive train with much more uniform properties, and so less variation in drive force, and better timekeeping. By 1600, the most advanced small clock frames were being made of rolled brass strip, cut to length and fixed with standard screws in tapped holes.

If the drive to the foliot were exactly the same at each swing, it would keep perfect time, but variations in the drive, mainly due to friction, produce variations in rate. The most dramatic advances in performance came in a series of three experimental clocks by Jobst Burgi, produced for astronomical observation, which reportedly were accurate to better than one minute per day[35]. This was achieved by crafting the drive from the minimum number of wheels, thus reducing its variable friction, and using a weight drive that was automatically wound up by a spring at frequent intervals (a *remontoir*). The foliot excursion was fixed by rigid stops, and the weights were mounted on flexible

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[34] Joan Day, "Brass and Zinc in europe from the middle ages until the nineteenth century", in *2000 years of zinc and brass*, British Museum Occasional Papers Number 50, ed P.T Craddock, (London, 2000), pp133-158, p. 142; Mark Headrick, "Origin and evolution of the anchor clock escapement", *IEEE Control systems magazine*, 2002, 4: 41-52, p. 43.

[35] Hans von Bertele, "Precision Timekeeping in the Pre-Huygens Era", *Horological Journal*, 1953, XCV: 794-816.

arms which cushioned the stop and gave a spring element in the return, like the bristle limiter did.

Although the foregoing paragraphs show that the pendulum was introduced into a clockmaking world that had advanced technically in many ways, it is important to realise that these advances did not adhere in all manufactures. Examination of seventeenth century clocks shows mechanisms of very different technical refinement, all constructed within forty years of each other. The fineness of the mechanism can be gauged from the tooth pitch of the gears: The Dover Castle clock, the English Iron Lantern clock, and the Coster clock[36] have gear teeth of 15mm, 3mm and 1.5mm pitch respectively. The first two are foliot or balance clocks, and the latter is the Huygens designed pendulum clock. Although clocks of great refinement existed at the time the pendulum clock was introduced, only the advanced clockmaker could have successfully assembled one. The key property of the foliot that the pendulum does not possess is that of being self starting: if the drive to a pendulum is not sufficiently uniform it stops, until manually restarted. A similar drive to a foliot will produce an inaccurate timekeeper, but not a dead one.

The pendulum appeared in clocks from at least two distinguishable sources: one as a mechanisation of the free or hand operated pendulum used for astronomical and other scientific observation, the other as a modification of the existing foliot mechanism. Huygens reports the labour and tedium of timing observations by the pendulum in a heartfelt manner in *Horologium*[37]:

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[36] On display in the Science Museum, London, Inventory numbers 1884-81, 1954-579 and 1980-108 respectively.

[37] Christiaan Huygens of Zulichem, *Horologium* (The Hague: Adrian Vlaqc) 1658, Trans. Ernest L. Edwardes in *Antiquarian Horology*, 1970, 7 p.2, or at http://www.antique-horology.org/_Editorial/Horologium/

“ […] the astronomers initiated this method: that they should impel manually a weight suspended by a light chain, by counting the individual vibrations of which just as many should be included as would correspond to an equal number of time-units […] But besides the necessary motion of the pendulum failing unless repeatedly by the attendant, a further tedious task was the counting of every oscillation; to this end, indeed, some kept vigil for whole nights with the most wonderful patience, as they themselves testify in their publications. I […] sought by what means it was possible to attain this result in the shortest manner, and so find a remedy to the double inconvenience we bore.”

Huygens understood the causes of errors in the conventional foliot or balance quite well[38]:

“I have so far explained the matters pertaining to the construction of the mechanism; it remains to make clear how greatly it excels all others which have been used up to the present time. The causes of very many of the uncertainties and inequalities in these are sufficiently well known. Thus even the smallest fault in the due arrangement and polishing of the wheels is followed by a notable inconstancy in the continuous movement. Then, indeed, by the oil which it is customary to add to the pivots, drying and vanishing, the clock goes slower, and notwithstanding, the absence of these inconsistencies, clocks are sensitive with cold, for example, the commonly exhibit sluggishness; equally with heat, they go faster.”

This indicates familiarity with the foliot clock, its manufacture and maintenance. He goes on to rather overstate the powers of the pendulum:

“It is true nature and poverty of a pendulum that it will necessarily always maintain uniformity, from which it will never deviate unless the length be altered; it is evident, therefore, that by my invention I have removed altogether those inconveniences to

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[38] *Horologium* p. 5.

which I have referred, so that unless it happens that by some impediment the timepiece is stopped, no slowing or inequality of the motion need be feared.”

This is immediately qualified:

“First, it may be noticed that mine differs from the free pendulum because with every vibration it receives a momentary contact and impulse [the drive input] from the crutch QR. Then, although it retains the properties of the simple pendulum, producing all of them, notwithstanding this some have observed in it double inequalities for which they have searched minutely. This because the truth of the contact with the crutch is not to be denied. But we know it is very gentle by reason of the weight T [the pendulum weight], which so governs the whole it not only controls the movement of the pendulum but also minimises the extent of the constant arc in the same way. Consequently the crutch of itself produces nothing violent or less equable in the movement of the pendulum than if the motion were not wholly beholden to it, and the pendulum SIT simple, and impelled, as hitherto was the custom, by hand, This, indeed, the best experience confirms. The two inequalities observed in the pendulum itself, however, some deny altogether; of these, one I admit, but it is scarcely prejudicial to my timepiece.”

This is as good an intuitive and empirical explanation as could be expected for such a complex system as he had devised. The motions of both the pendulum and foliot are actually determined by the condition that for each cycle the work input from the drive is equal to the work lost by the oscillating parts (as friction, air resistance, etc). The leading errors in timekeeping arise because the input or the loss changes, usually due to changes in frictional resistance. The loss increases with speed of oscillation, so, for example, a reduction in drive, due to the causes Huygens remarks on, will produce a reduction in speed. The foliot is arranged with a restoring force no larger than the drive force[39], so the period is strongly dependent on the drive input. The Huygens pendulum is arranged so that the restoring force due to gravity is much larger than the drive, and its period is thus largely determined by gravity. This arrangement is obtained by suspending the pendulum from a pair of threads, which gives much lower friction and wear than a pivot; the low level of this friction is why the drive may be so gentle, and why Huygens argument is sound. The escapement has to be mounted on pivots to define its geometry: it's connection to the pendulum is effected by a crutch embracing the pendulum rod. From this and other communications[40] it is clear that he has a sound grasp of the roles of the drive, the friction and the weight in obtaining the best timekeeping, although they were, of course, well beyond a rigorous analysis.

Huygens goes on to deal with the well known increase of period of the free pendulum at large angles of swing, and explains that in his design the effect is reduced because, even though the escapement requires a large angle to operate satisfactorily, gears placed between it and the pendulum allow the pendulum angle to be small. His argument is again sound, and again approximate. Huygens had previously developed an alternative means of reducing this effect by suspending the pendulum from a pair of threads confined by curved cheeks, which shorten the pendulum progressively as the angle

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[39] von Bertele, remarks ("Precision Timekeeping", p803) that the suspension cord of the foliot affects its motion, but only insofar as it is not perfectly flexible, and he neglects the effect in his analysis. A more significant effect arises from the bifilar nature of the suspension which contributes an approximately linear restoring force. This would be expected on theoretical grounds to improve the timekeeping, but this has not been tested experimentally. Foliots are self starting, which places an upper limit on the possible restoring force. An interesting design alternative, feasible at that period, which does not seem to have arisen historically is to modify the bifilar suspension to produce a natural period equal to the design period of the foliot, thus obtaining the mechanics of pendulum operation. Such a design would not be self starting.

[40] Bell, *Christian Huygens*, p. 129, Landes *Revolution in time*, p. 117.

increases[41]. The cheeks were abandoned for *Horologium*, because of the resulting sensitivity of the period to any accidental tilt of the clock.

There is some evidence that contemporary clockmakers were developing pendulum mechanisms[42], as modification to the foliot. For makers such as Fromanteel and Campani, whose foliots oscillated about a horizontal axis, this would be very straightforward: the upper half of the foliot only has to be omitted. The result is an introduction of a substantial gravitational restoring force into the motion, and so a reduced dependence of period on drive force, and improved timekeeping. These makers were also fine enough workers to enable a successful product. This development is a significant one, because it breaks with the convention of being self starting. Once this break has been made, there is no obvious obstacle to these mechanisms evolving towards the more freely suspended pendulum, since that would be found experimentally to offer superior durability, and timekeeping. Any such development was, of course, preempted by Huygens design, which had the free pendulum concept from the outset.

In the later *Horologium Oscillatorium*[43] Huygens describes a clock using the curved cheeks. He has by this time completed his mathematical demonstrations that a pendulum following a cycloidal path has a period independent of amplitude, and that the cheeks will, for an idealised geometry, generate that path if they are cycloidal themselves. His statement on the correctness of the timekeeper has changed, though:

“It is quite evident that the motion of the pendulum VX, after it has first been started by hand, is sustained by the force of the wheels which are pulled by the weight, and also

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[41] Yoder, *Unrolling time,* p71 and p204 n.1.

[42] Keith Piggott, “The Coster-Fromanteel contract: its continued place in modern scholarship”, at http://www.antique-horology.org/

[43] Christiaan Huygens, *Horologium Oscillatorium,* (1673) Trans. Richard J. Blackwell *Christiaan Huygens’ the pendulum clock,* (Iowa State University, 1986) p. 16.

that the periodic swings of the pendulum lay down a law and a norm for the motion of ail the wheels and of the clock as a whole. For the small rod S, which is moved very slightly by the force of the wheels, not only follows the pendulum which moves it, but also helps its motion for a short time during each swing of the pendulum. It thus perpetuates the motion of the pendulum which otherwise would gradually slow down and come to a stop on its own, or more properly because of air resistance. On the other hand, the nature of the pendulum is such that it always moves in the same path and cannot be changed from that path in any way except by changing its length. Furthermore, after we have attained the equality of motion, mentioned above, which is due to the curvature of the thin plates between which the pendulum is suspended, the wheel K is not permitted to move faster or slower, as it often tends to do in ordinary clocks. Rather each tooth of K must move along in an equal time. From this it is clear that the rotations of all the preceding wheels and ultimately of the hands of the clock are made uniform, since ail of them are moved proportionally Hence, even if there is a defect in the construction of the clock or if the axes of its wheels revolve with difficulty because of a change in the condition of the atmosphere, still, as long as this is not so great as to stop the clock completely, there need be no fear that its motion will be uneven or slowed down. It will always measure the correct time, or else it will measure nothing at all."

He appears to believe that there is no effect of the drive on the motion of the pendulum. It is not clear how, having had the earlier sound insights about the influence of the drive, he might later have dismissed them. *Horologium Oscillatorium* is largely devoted to his great achievement of the mathematics of cycloidal motion and of evolutes, providing a theoretical underpinning for the clock design. The technical innovation that was key to the success of the pendulum, the separate suspension, is not discussed; instead, there is a mathematical focus, one that remains to the present day[44]. Perhaps his concentration on the ideal pendulum, and his theoretical successes in eliminating circular error, made it hard to accept the remaining blemish on the machine's perfection. Perhaps he did not wish to undermine the impact of his publication by betraying a possible defect which, after some future exact analysis, might turn out to be nonexistent, or easily sidestepped in practice[45]. It would have been straightforward for him to carry out experiments to examine the effect of varying the drive forces, but the results would not necessarily have provided a clear view of what was going on. It would be illuminating to use the description of the clock in Horologium Oscillatorium to estimate theoretically how large the drive effect was for his machines, but unfortunately the data Huygens provides cannot be reconciled with a consistent picture of the situation[46].

None of the developments described above sought to modify the mechanics of the verge escapement[47], which is the mechanism most particular to the clock. Huygens' earlier use

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[44] Neither H.J.M. Bos (in his introduction to Blackwell's *Horologium Oscillatorium*, pp xi-xviii) nor Joella Yoder in *Unrolling Time* refer to the drive effect.

[45] It is possible in principle to eliminate the effect of the drive on period by applying it symmetrically to the motion. This appears impossible in practice, but the detached escapement in a watch gets close.

[46] The earlier Coster clock runs at an amplitude of about 13º, which is at the lower limit of what is possible with a verge escapement, and rather too low for long term reliability. Assuming the same amplitude, and making favourable assumptions about efficiency and losses, the drive weight he reports for "the best clocks we have to date" is several times too small to sustain the motion. His reported drive weight is credible for a high quality carefully maintained anchor escapement clock of that date, which operates at about one fifth of the amplitude. For such a clock the effect of the drive is to change the rate of the clock by about one minute per day, and the change due to amplitude is about six seconds. For a C20 regulator clock with deadbeat escapement, the changes from each cause are both about three seconds.

[47] Burgi's cross beat rearranges the verge so that it can be driven at one side of the escape wheel, since the latter was so large that retaining a conventional verge would imply a shaft of excessive length, and flexibility. The mechanics of its action against the escape wheel remain the same as with a conventional

of gears between escapement and pendulum enables use of a small swing in a way that avoids technical innovation: it is achieved by interposing a known working device to a calculated effect. The anchor escapement, developed immediately after[48], gets the same result by modifying the verge so that the pallets are on lever arms of suitable length, which amplify their movement. This arrangement involves more sliding, and so more friction, than the verge, and needs more care with geometry, construction and materials. Its form can be arrived at by systematic technical thinking about morphological and geometrical changes to the verge. The threads suspending the pendulum gave inadequate constraint to its motion, and were replaced by a minimal flat spring by 1671; this brought about the design that was to last, for domestic and small commercial pendulum clocks, until the present day.

The subsequent development of more precise regulator clocks, and of seagoing chronometers is a story of ceaseless technical activity, based, like the earlier developments described here, on observation, experiment, suitable approximate understandings, systematic technical thinking, and enthusiastic employment of technical innovations. Performance was achieved by the minimisation of friction, the control or elimination of lubrication, the reduction of drive variations, and by temperature compensation, all of which were considered by Huygens in his early work.

The mathematical analysis of escapements and the effect of their drive on period was achieved analytically, in an approximate form well suited to clocks, by Airy in 1830[49]. It provides a useful explanation of the properties of actual escapements, but I am not aware of it having been used to guide a design. For an adequate analysis of a real

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verge.

[48] Eric Haswell, *Horology*, Chapman and Hall, London, 1947, p. 166.

[49] George Biddell Airy, "On the Disturbances of Pendulums and Balances, and on the Theory of Escapements." *Transactions of the Cambridge Philosophical Society*, 1830, Vol. III, Part I: 105-128

mechanism it requires numerical solution, which only became convenient with electronic computers. It appears that the manufacture and repair of mechanical clocks today is based on configurations and techniques that have been established by technical activities.

ROLES AND THEIR RELATIONSHIP

We can now look over the interplay of scientific and technical activities in the development of mechanical clocks. A clear and repeated effect of scientific activity is in providing motivation and reward for the development of more accurate timekeepers: Burgi, Huygens and Airy were all seeking superior performance for use in astronomical observation. For this, a high cost could be afforded, maintenance of the highest quality was available and reliability was of little importance, and operation was static: the pendulum was the solution. There were other markets for timekeepers, with different requirements: commercial and domestic machines had to be reliable, cheap to buy and maintain, but not so accurate, for which the foliot was generally appropriate until the renaissance period. For the longitude problem, accuracy and mobility were essential, but initial cost and maintenance could be much higher.

An equally clear and repeated effect of technical activity has been of the materials and manufacture for timekeepers. The development of this infrastructure controls what is possible in making artefacts; this development is poorly recorded, and problematic to study. Much can be gained from the examination of artefacts, but the story can only be filled out with conjecture and imaginative reconstruction. Alongside these effects is the emergence of clockmaking as a widespread trade: although it was secretive and protective, the trade was the parent of the technical advances and systems of manufacture that made Coster’s shop, and made him able to execute the work for Huygens with success.

Another effect of scientific activity arose from the technical environment it generated: instruments were devised to improve observation, and their use and refinement involved novel techniques[50]. Huygens' clock design was a fusion of such a technique, the manual pendulum, with the reciprocating drive available from a mechanical clock. Obtaining this kind of step forward, by interdisciplinary fusion, is very familiar in design activities, and ways for bringing it about are part of design procedures[51]. The adaptation of a foliot to produce a pendulum effect was also a step forward, but was made without the extensive familiarity with the pendulum that directed Huygens firmly towards imitating that artefact in a way that, as far as possible, preserved its operation with minimal interference. Although Huygens had not completed his mathematical analysis of pendulum motion when the clock was designed, that was not an impediment to the step. In operating manual pendulums, it is evident that their motion is the repetition of the same pattern of movement, differing only by the slight change in amplitude as the swing dies away. With systematic use of contemporary techniques, this change can be reduced to a small fraction of a percent per cycle. After that experience, it is intuitively clear that a pendulum swinging without impediment, and so with unchanging amplitude, would repeat the same motion perfectly, whatever the details of that motion are. The experience also teaches that the more massive the pendulum, the less it is affected by external disturbance, just as a flywheel sustains its motion by its mass. These arguments were sufficient to generate Huygens design of a pendulum with a minimal drive.

The same kind of technical argument also led to the curved cheeks that remove the dependence of period on amplitude: given that period is observed to *increase* with amplitude, a geometric configuration to compensate is possible. Actually, Huygens configuration is not viable partly because it assumes that the pendulum rod and the

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[50] Robert Hooke, *Micrographia*, London, 1665.

[51] J Christopher Jones, *Design Methods* (London: Wiley, 1980), Section 4.

attached threads remain collinear at the point of attachment. The drive force destroys that collinearity, as can be seen from careful observation of the motion. The spring later used in place of the threads is also incompatible with the requirement in the design of the cheeks, that its curvature be infinite at the suspension point, and be discontinuous where it leaves contact with the cheek[52]. Huygens' later mathematical analysis of the ideal operation of the cheeks provided a way of generating the profile conveniently, but it is not evident that it was of assistance in the manufacture of an accurate clock. Strictly, of course, the profile was only correct for a single length of pendulum, so his provision for adjustment of that length removes the exactness of the analysis.

This mathematical analysis was in itself a scientific activity: it was in part a response to a mathematical challenge in geometry, and added to perhaps the most copious and highly intellectual of doctrines. It was presented as by far the most significant part of the publication, and continues to receive the greatest attention. It's immediate effect on technical development seems to have been rather negative, in that it was accompanied by the erroneous removal from consideration of the drive in the analysis of timekeeping. This view has endured: the education of present day scientists and engineers conveys that the length of the pendulum determines timekeeping, and it is only specialist horologists who know otherwise. Another problem with linking technical development to an advance in mathematics is that the analysis is complex, and only accessible to a specialist. Huygens' concern is to carry out rigorous proofs, which are valid only when their assumptions are exactly true. In these circumstances, insights into how real mechanisms work can be obscured, rather than deepened. From the technical point of view, such a link may prove a discouragement to the use of mathematics in technical

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[52] A L Rawlings, *The science of clocks and watches* (Upton: BHI, 1993), p. 60

development, and sustain the opinion, still surviving, that mathematical analysis is of little use in innovative design[53].

CONCLUSION

The above account of the relationship between scientific and technical activities in the development of mechanical clocks has relied on taking care with the categories used, so that refined, quantitative and systematic technical activities are regarded as just that, and not labelled as science. With this approach, the relationship is seen to have strikingly modern features. These include interdisciplinary fusion to obtain technical advance, science as a patron of technical advance, systematic and rational technical activities that are not scientifically understood, and a post hoc mathematical analysis that is given a leading role in contemporary and later accounts. The other episodes in early modern science outlined in the first section of this paper indicate that the same approach could reveal modern features in them as well. To establish this continuity more generally is well beyond the scope of the present paper, but if it were so, it would appear that the increasing refinement of technical investigations in the various industrial laboratories set up since the beginning of the nineteenth century is not due to an injection of scientific values, but is an organic development of an antecedent practice.

The argument for broader continuity is supported by examination of the work of other individuals and institutions: quantitative and systematic technical activities are found (for rather parochial example) in the work of the early Royal Society of London, Hooke and Tompion, the Abraham Darbys, Harrison and Jefferys, Newcomen, Watt, Carnot, Wedgwood, Davy, the Royal Institution, Faraday, and Heaviside. To be sure, the relationship between science and technology becomes far more elaborate over this period, and the role of mathematics matures. The relationship between the concepts of

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[53] James Dyson *Against the odds* (London: Orion, 1997), p. 112.

Hooke and the mathematics of Newton is echoed in the relationship between those of Faraday and Maxwell, but appears in a greatly more developed form. The maturation of mathematics is seen, for example, in the development of the work of the latter pair: the work of Heaviside, which is both an advance in mathematics and a thoroughly technical activity. The mathematicistation of nature changed our view of mathematics as much as it did our view of nature.

The role of science in the establishment, maintenance and delivery of doctrine also develops, via the development of scientific research in the universities, the linkage between research and teaching, and the links between the latter and the educational curriculum. This has profound cultural effects, in the attitudes of practitioners, on the distribution of funds, on lay perceptions of science and technology, and on how historians of science think. As Floris Cohen says: "Still it may be gathered […] that around 1600 new protagonists came on the scene, and that they have stolen much of the show ever since."[54]. Actually, they they were in the company that owned the show at the time, and have kept firm hold of it ever since.

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[54] Cohen, *The scientific revolution*, p. 353.