H. Floris Cohen

The Rise of Modern Science as a Fundamental Pre-Condition for the Industrial Revolution

Abstract: No viable account of the rise of the modern world in 19th century Europe can do without an account of the emergence of modern science in 17th century Europe. The indispensability of the latter event for the former has often been ignored, or denied, or maintained on needlessy shaky grounds. In this paper the author seeks to ground the historical conception of 'no Industrial Revolution without a preceding Scientific Revolution' in rigorous argument. It takes its starting point in the engine that James Watt was in due time to transform into the steam engine, namely, Thomas Newcomen's fire engine. The author demonstrates that at the very heart of his machine Newcomen employed, and could not but employ, revolutionary knowledge of the void and of air pressure. He also shows how sophisticated knowledge of this novel, modern scientific type stood squarely athwart such more commonsensical notions as used to mark rival efforts, be it earlier in Europe or in China or elsewhere, to come to grips with the phenomena of nature. The Newcomen engine further serves to show how the 18th century provided something like an 'incubation period', in course of which mostly British artisans of a wholly novel type learned by trial and error to bridge the vast gap between the theoretical solution to some practical problem and a truly viable, truly practicable solution.

Key Words: Scientific Revolution, Industrial Revolution, Economist Millennium edition, fire engine, Needham problem

The lead-text for the paper that follows is a 3-page piece entitled *The Road to Riches*. It appeared at a prominent place in the special 'Millennium' issue of the *Economist*.[1] That special issue was built around a splendid idea. Take your vantage point at the previous millennium, in the year 1000 AD, and look a thousand years ahead – there is no possible way anybody in his right senses could have foreseen what our modern world of the year 2000 was going to look like. Even less could it have been predicted

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at the time that Western Europe is where the big leap toward that modern world of ours was to occur. At the start of the first millennium there were several advanced civilizations, by and large on a par mutually, with Europe appearing as rather a late-comer among them. Certainly at first sight it is a profound enigma why, of all civilizations then around, it was this late-comer that, some nine centuries down the line, was the one to make the unexpected leap. In the three pages of *The Road to Riches* its (as always with the *Economist*) anonymous author faces the enigma squarely, and probes a number of possible solutions. He does not seek refuge in just one cause that allegedly explains it all. Nor do we encounter learned elaborations upon simple-minded one-liners about Westerners being more logical or having better genes or some other allegedly built-in, timeless superiority. Even better, his answers are also far removed from the other extreme of regarding the question of where the leap occurred as just a matter of chance not subject therefore to any deeper historical analysis.

In its first-rate journalism, then, this 3-page piece *The road to riches* provides a particularly good example of a sophisticated approach in which one cause, no cause, and cheap sloganizing are being shunned alike. Instead, we find some lucidly and succinctly rendered fruits of genuine, also wide-ranging, boldly comparative historical analysis. The piece opens with the observation that modern science and technology serve as powerful motor drives for *present-day* economic growth and social change. Therefore it seems an obvious move to seek what *originally* brought about the European leap likewise in science-based technology, with its meanwhile proven capacity for social change of the most drastic kind.

That answer sounds plausible – so the argument in *The Economist* goes on –, and it is unlikely to be entirely wrong. Still, it fails to satisfy, on at least three significant counts:

(1) Up to Edison's times around 1875, the huge majority of industry-promoting inventions, such as Hargreaves' spinning-jenny at an early stage, owed virtually nothing to science.

(2) In the 17th century, pioneers like Galileo or Huygens or Hooke made rapid advances in science. They were keen to find applications for their finds and have them exploited in practice. But if these finds had indeed been so decisive, whence, then, the passage of at least a hundred years to come until industrialization even began to take off?

These two points lead to an interim conclusion, which reads: "The link between science and technology is subtler than you might think." But a further objection to any straightforwardly causal connection between European science and European industrialization is raised in addition:

(3) Other advanced civilizations, too, experienced periods of brilliantly flourishing science and/or technology. This was true notably of China before, under the Qing, it lost its lead for good. At least in the Chinese case and possibly in others, too, these advanced civilizations came to the very brink of industrialization, yet they never managed to cross it.

The net conclusion drawn in the article at this point is that "science and technology, in short, can get far and then stop". Consequently, the truly crucial question should run thus: "What happened in Western Europe in the 17th and early 18th centuries that failed to happen in the Western Europe of antiquity, or in China after 1400, or in the Islamic world after 1200?"

At this point of high suspense the article makes a turn that does not cease to amaze me. Without any breathing spell it goes on to tell us that "the question is ferociously debated by economic historians". And once again without any pause or interruption, this leads on the final page to a once again quite knowledgeable discussion of the "three broad and overlapping things [that], between them, made the difference: values, politics and economic institutions." Nowhere in this concluding section does either science or technology, let alone the "subtle link between them", re-enter the scene. True, objection (3) implies that they cannot do so as *independent* variables. But the coherence of the overall argument requires in no way their absence as *dependent* variables.

Nor is this the only ground for surprise at finding the role of science and technology in the making of the Industrial Revolution ignored from that point onward. For if we confront the conclusion thus drawn with the very consideration placed at the head of the piece, an odd paradox ensues. It now seems as if modern science & technology, which the author himself has just acknowledged to add very substantially to all that at the present day drives our modern society forward, nonetheless, in being neither 'values' nor 'politics' nor 'economic institutions', had nothing at all to do with how modern society originally came into being. That is, 'values', 'politics', and 'economic institutions' jointly ushered in the modern world, subsequently to unfold under the steam of science-based technology. Not a very plausible course of events, to put it mildly. What, then, has been the point of calling attention in a serious work of history to a mere journalist's sloppy reasoning?

One reason for spending time on the issue is that we had better not think of journalists in terms of 'mere journalists'. Not only do the contents of *The Economist* reach a vastly larger, politically far more influential readership than any scholarly effort to set its conclusions right may even begin to hope for. But we should also realize that what we have here is really journalism at its very best, not only for the reasons I have just given in my second and third paragraphs, but also in that it reflects, and ably sums up, a good deal of current, scholarly thinking on the subject.

Whose thinking? Well, chiefly economic historians' thinking. The curious dichotomy between economic history and history of science & technology that the *Economist* piece displays is nothing but the reflection of a dichotomy that reigns in the world of scholarship. In *The Scientific Revolution. A Historiographical Inquiry* of 1994 I have gone out of my way to deplore that professional historians of science have usually treated the emergence of modern science as "a secret treasure".[2] Decades ago, historians of science have illuminatingly conceptualized the emergence of modern science in 17th century Europe and elucidated what was so uniquely novel about the kind of science that did emerge. Yet with few exceptions they have failed to link this up other than in slogans with what the event has meant for the coming into being of our modern world. Indeed, the common run of historians of science has chosen to ignore that world-historical problem and to marginalize the few who have not. Consequently, a problem that really requires the expertise of just about all varieties of historians (political history and the history of religion definitely included), has become to a very large extent the domain of economic historians alone. I certainly do not want to begrudge them their concern. To the contrary, it is altogether a great boon that at least in one specialist discipline the problem has remained alive. The more so as this happens also to be the one where sophisticated, analytical-comparative thinking has advanced to far greater heights than in any other branch of history. Further, an increasing number of chiefly economic historians has in past decades been crossing these borders – the names of Landes, O'Brien, Mokyr, Goldstone, whatever their mutual differences, come to mind at once. Still, look again at the three specific objections that in *The Road to Riches* led its author to exclude modern science & technology from the story of how the world got modern and rich. These objections are in truth far from sloppy. Even so, to find out what is tenable about them and what not requires a bit more familiarity with findings made by historians of science & technology than most economic historians possess as a rule.

My aim in the present paper, then, is to confront all three objections advanced in that *Economist* piece. I do so from the point of view of a historian of science concerned to understand certain major issues concerning the rise of modern science in 17th century Europe – its major components; how it could come about at all; how it is that it did so in Europe rather than elsewhere; what it meant for traditional craftsmanship on the shorter and longer run, and what it has contributed to the coming into being of our modern world.[3] In discussing the issues that are raised by the three *Economist* objections, I take the harnessing of steam power to be indispensable for arriving at a fair judgment of the piece as a whole. This is so because the story of steam helps us see

- why objection (1), albeit not entirely mistaken, is an exaggeration that amounts to distortion;

- how to rephrase, and then answer, the very good question posed in objection (2);
- why objection (3) is untenable, with consequences.

In *The Road to Riches* the author has not, to be sure, quite ignored the pertinence of steam power for his argument. In regard of his objection (1), he does mention the steam-engine (albeit without any further explication or discussion of consequences for his own argument) as one exceptional piece of science-based technology prior to Edison's times. In regard of his objection (3), he very strongly suggests (without quite committing himself) that in China even earlier than in Europe all the knowledge about atmospheric pressure that one might need to build a steam-engine had already been discovered without that knowledge actually being tapped for going ahead and constructing such a machine. Only in regard of (2), on the application-oriented science of Galileo and Huygens and Hooke and its failure for at least a century actually to be applied, does the author fail to mention steam power as an example, even though well he might have; as we shall see.

Where exactly, then, does the *Economist* piece go wrong in its effective downplaying of what all that happened in science in 17th century Europe truly meant for the process of industrialization? To show you where, I take you inside Newcomen's engine. Although in so doing I aim to make you consider it afresh, in my brief explanation of how it works I claim no novelty whatsoever – it is all there in the literature on the history of steam technology,[4] only the message of that literature does not seem always to get out to those whom it concerns.

Newcomen's engine, from the outside in

To ease your entrance, I start from the outside (see Figure 1).[5]

Note that the caption does not speak of a *steam*-engine, but rather reads 'The ENGINE for Raising Water (with a power made) by Fire'. Also note that, thus looked at from the outside,

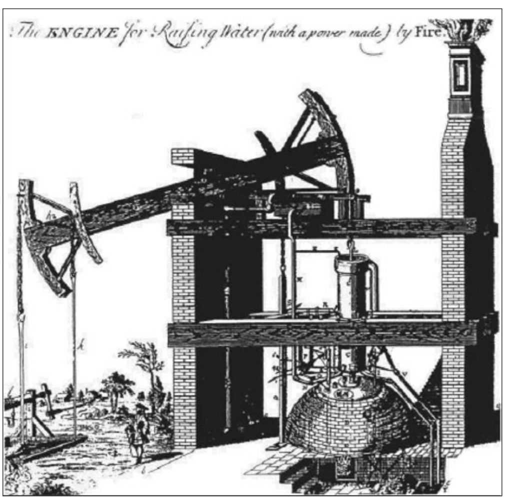

Figure 1: Newcomen Engine

there appears to be nothing in its construction that seems principally out of reach for any comparably daring inventor in any comparably advanced civilization of the pre-modern world.

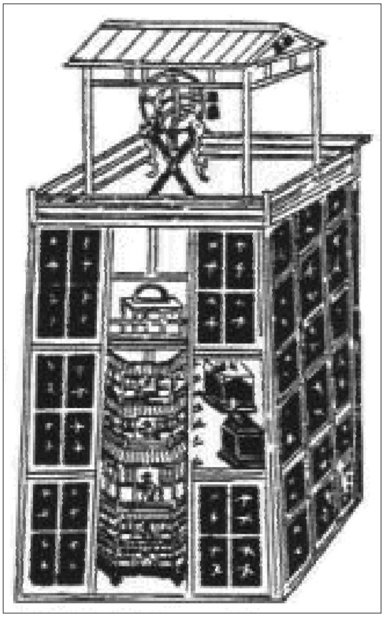

Figure 2: Su Sung's Water Clock

Figure 2, for example, is a wood-block engraving of Su-Sung's huge water-clock regulating the course of the planetarium-like armillary sphere on top of it.[6] This invention, by a high official of the Northern Sung dynasty, dates from the late 11th century CE. Looking at all this from the outside, no good reason presents itself for why a civilization capable of both inventing and building so sophisticated a piece of machinery could not in time have produced a fire-engine like Newcomen's or even the kind of steam-engine Watt later transformed it into.

We now move further inside. In Figure 3,[7] note first the big balance beam, with the mine pump rod hanging from a chain on the one side, and a piston on the other. The rod enables suspended buckets to pump water out of Britain's coal mines, which is what the machine was made for. The piston fits closely into a cylinder which can be filled with steam from the boiler below, in a cycle regulated by the steam-valve in between. Also suspended from the balance beam is a small pump, allowing the cold mine-water it raises to be used for being sprayed into the cylinder. This likewise happens in a cycle, regulated in this case by the injection water cock in between. Finally, water leaves the cylinder through an eduction pipe and air leaves it through a 'snifting valve'.

We must grasp next how this assembly causes the balance beam to make the mine pump rod go up and down and thus empty the mine of water. So we move farther inside the engine, and seek to understand what the picture can no longer show. The effect of spraying cold water into a cylinder filled with steam is to condense the steam, thus leaving a vacuum inside. Consequently, the atmosphere presses down the piston, so that the mine pump rod is pulled upward. With the injection water cock shut off and the steam-valve opened, fresh steam enters the cylinder, the piston is pressed upward, and the process can repeat itself, up to some fifteen cycles per minute in practice for more than a century upon the engine's invention around 1710.

The invention did have a prehistory. Slightly prior to Newcomen, Denis Papin (earlier Christiaan Huygens' assistant in Paris) communicated a sketch to the Royal Society. This is significant in view of three distinct features of Newcomen's invention. One is that Newcomen, not a scholar but a a skilled craftsman, is improving here upon a scholar's proposal – a practice-oriented scholar to be sure, yet a scholar. Newcomen introduced a separate boiler rather than, as Papin had proposed, putting a fire under the cylinder but the water in it. A second feature is Newcomen's genius as an inventor, which stands expressed in the presence of the snifting valve and, above all, in the automated snap-action of the injection cock and the steam-valve. It is these two features that turned the theoretical and, as such, unworkable solution to a practical problem that Papin had proposed into a truly practicable solution, into one that really could work, and did. Finally, the third feature concerns the unseen heart of the machine, the process of deliberately creating a void so as to enable atmospheric pressure, rather than horses or your fellow-man, to do work for you. What we have here is something transcending in a principal manner mere pre-modern craft ingenuity however admirably ingenious at its best. I have just called Newcomen a genius. But both previously and later, both here and elsewhere the world has known technicians blessed with equal gifts. What, then, is so special about this fire-engine by Newcomen to make it the first product of technical ingenuity decisively different from, say, the medieval mechanical clock, from Su-Sung's water clock, from Chang Hêng's seismograph, or from al-Razi's distillation vessels?

Revolutionary science in the engine

My answer to this question is fourfold. It is that at the heart of the machine we find the incarnation of a scientific idea – an idea made flesh; an idea explicitly formulated and deliberately applied. It is, next, that that scientific idea, which is about the possibility of void space and of experimental proof for the effective voidness of certain spaces, was entirely unheard-of, without any precedent anywhere. It is, further, that that unprecedented scientific idea runs counter to any common-sense conception of nature. And it is, finally and most importantly, that that novel scientific idea is not just an isolated, bright idea such as may come up as a matter of course in some chain of ongoing, regular scientific advance, but is just one sample of something principally novel occurring at the time. This novel thing is that the body of ideas and practices out of which the recognition, creation, and effective proof of the void came forward alongside much, much else, comes down to a well-prepared and nonetheless quite radically novel mode of thought about nature as such.

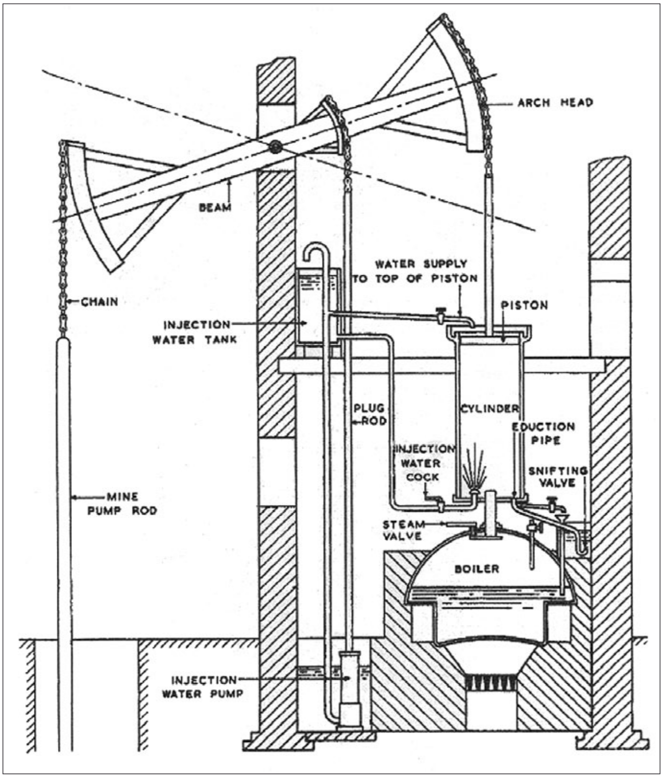

Figure 3: Diagram of Newcomen Engine

This mode of thought is that of modern science as it first came up in a – to us at present – *grosso modo* recognizable way in 17th century Europe. This mode of thought about nature has in its broad outlines become quite routine to us nowadays; at the time, however, it looked extremely odd, menacing even, in that it went flat against a whole range of conceptions shared across cultures the entire pre-modern world over. For the first time, nature began in 17th century Europe to be addressed on a principally novel plane. That plane was neither a one-sided empiricism, with facts taken from everyday sense-perception and sheer common-sense and then arranged in orderly patterns on the same level of sense-perception and common-sense. Nor was it an even more one-sided intellectualism, with everyday observations of nature pressed into one or another set of all-encompassing, philosophical first-principles deduced *a priori*. Instead, a thoroughly *counter-intuitive* mode of nature-knowledge at a plane of understanding unprecedentedly intermediate between abstract philosophy and plainly concrete common-sense observation came up in 17th century Europe. This mode of nature-knowledge was both immensely more *reliable* and, at least potentially, more *useful* than was true of any preceding mode of acquiring knowledge about nature.

The vastly increased *reliability* of the mode of nature-knowledge that 17th century Europe began to pioneer, and the very principal reasons for it, are at the heart of what the *Economist* piece so tellingly overlooked.[8] The vastly increased *usefulness* of the new science, as the *Economist* piece noted well, was apparent to many a pioneer right from the start. The trouble, as it also noted, was that useful application of a whole range of novel insights kept eluding them in almost every instance. This is true of nearly all those promising plans put forward over the entire period of the Scientific Revolution from Galileo up to Newton. Be it the harnessing of atmospheric pressure by making water boil on the bottom of a cylinder and then allowing it to condense by putting out the fire underneath (Papin, elaborating upon Huygens, von Guericke, Pascal, Torricelli, and Galileo), or the attempted, scientific regulation of water streams (Castelli, elaborating upon Galileo), or efforts to make the deaf hear again (Hooke, elaborating upon Bacon), or even to produce artificial manure out of wood juice (Glauber, elaborating upon Paracelsus), it all came to naught.

Why did it all come to naught? Here again the *Economist* piece is quite right: the link between science and technology is subtler than we tend to think. More than that, prior to the 17th century Scientific Revolution there was scarcely any link at all. The kind of nature-knowledge that we can see by hindsight to have been applied in practical tools and machinery used to be intuited; as a rule, it was neither derived from, nor supported by, any available body of nature-knowledge. We can see for instance how the construction of certain stops in late medieval organs brilliantly exploited properties of the so-called overtones, or harmonics. Yet the very beginnings of acoustical knowledge of those harmonics, i.e., their one-by-one identification as such, did not even begin to take place until more than a century later, in the ears and the quiet monastery of Father Marin Mersenne early in the Scientific Revolution.

To find out how the customary chasm between nature-knowledge and the crafts gave way to the kind of science-based technology that we tend to take for granted nowadays is among the most neglected empirical issues central to the Scientific Revolution. What hurdles were being encountered in practice, and what enabled scholars and craftsmen of later times to overcome them?[9] I have made an all-across-the-board survey, focused in particular on 17th century efforts to make *mathematical* science practicable.[10] Here are some conclusions.

Between the Baconian dream and its realization

What is a machine? During the European Renaissance, prior to the birth of modern science, artisans out to improve the operation of, for example, saw-mills or water-wheels regarded these as composites of individual parts to which, so as to enhance their effect, one might add further parts at will. As one truly precocious exception, Leonardo da Vinci alone began to perceive, in the privacy of his handwritten notes, that machines are rather assemblies coherently made up of an identifiably circumscribed number of constructive elements. His desire to optimize the effect of machine tools was guided by an awareness that what one gains one way is necessarily lost another. This led him toward no less exceptional ranges of experimental researches into possible chances for minimizing friction.[11] About a century later, Galileo unwittingly took his departure in the very same fundamental insight into the nature of machine tools, so profoundly at variance with most craftsmen's received wisdom on the subject. Instead of Leonardo's early, fact-finding experimentation, Galileo characteristically went on to pioneer the other, mathematical component of the beginnings of a theory of optimal engineering practice. He did so by arguing that all machines are jointly reducible in the end to the law of the lever. Here is how one rare historian of technology-*and*-science, the late Donald Cardwell, expressed the major practical change thus wrought in theory:

> "How could one possibly compare a fulling stocks with a corn mill, a saw mill with a blast furnace, a mine pump with a pump for supplying a mansion with water? All of them did entirely different things and the only common question to ask was whether each machine served its purpose well. The answer […] could only be normative: it was a good machine or it was not. But according to Galileo's arguments all machines, no matter what purposes they serve, have the common function of transmitting and applying 'force' or power as efficiently as possible and, moreover, the performance of machines can be quantified, for ideally the product of the driving 'force' and its velocity equals the product of the load multiplied by its velocity."[12]

This was truly an insight with (on the longer term, to be sure) world-shaking significance. Here we watch the domain of common-sense and rule-of-thumb driven craftsmanship being drawn into the counterintuitive, all-disturbances-removed, ideal-case domain of modern, mathematical science which Galileo pioneered. Single-handedly, Galileo showed that

> "a machine croaking and groaning under its load is not, in spite of appearances, necessarily doing the most work, [in that Galileo] saw that the inequality between the equilibrium force and the force required to set the machine in motion was not a principle of Nature; it is merely a consequence of the imperfection of all machines. A good machine will move at a uniform, unchanging velocity when the force and the load, including residual friction, are in equilibrium. A perfect machine, free from friction, distortion and other

defects, will accelerate (slowly if loaded) under an extremely small force until it reaches an infinite velocity."[13]

Even so it was one thing to set common-sense convictions right in theory; still quite something else to draw practical benefits from these and related insights. To make craftsmanship enter the domain of mathematical science was hardly tantamount to turn it by the same token into science-based technology. Not Galileo or his disciples, but Edme Mariotte in the second half of the 17th century pioneered an effort, to be undertaken with increasing frequency over the 18th century, actually to calculate (however often outcomes proved mistaken at first) the work capacity of, notably, water-wheels and, later, engines using steam for their source of power.

This, then, is my theme here – the vast gap customarily obtaining between pre-modern science and pre-modern craftsmanship; such chances for bridging that gap as were perceived right from the start in the early 17th century to be inherent in modern, Galilean, mathematical-experimental science; and, above all, the question of how realistic those expectations then proved to be on the shorter as well as on the longer term.

I shall now first pursue for a while this theme of mathematical science and the crafts. The mathematical handling of some scattered pieces of the natural world had flourished before in Hellenist civilization, which pioneered it, and in Islamic civilization, which adopted and enriched the approach. As compared with these two civilizations, Europe went much farther in exploring interfaces with the crafts. This was a highly unusual undertaking indeed. But for some legendary claims about Archimedes, and some actual applications of the law of the lever in pulleys and screws as described by Herôn, the highly intellectualist pursuit of knowledge of nature and the trial-and-error construction and improvement of such tools as eyeglasses or mechanical clocks went ahead in virtually watertight separation from one another. In this respect, the direct application of geometrical and/or arithmetical rules in linear perspective, in navigation and map-making, and in several military arts that took place in the European Renaissance was without world-historical precedent.

Even so we must consider that, by 1600, mathematicians had already come close to exhausting what they could usefully contribute to the creation of an illusion of painted space, to the outlay of fortresses, and to the determination of geographical latitude and the making of maps. So this might well have been the end of an interesting, relatively short-lived episode of collaboration between mathematicians and professional painters, soldiers, sailors, map-makers. But at this very point of imminent exhaustion a new vista arose from Galileo's conviction that our empirical world is at bottom mathematical, joined to his actually demonstrating how empirical phenomena like free fall and projectile motion can indeed be handled using mathematics. As he was well aware, a wholesale transformation of traditional craftsmanship had thus came within reach. How close was that reach? The promises that went with such expectations at the time were most often grandiose. Bracketing the promises, I have surveyed what achievements were actually attained in the dozen or so areas of craft activity actually subjected to some degree of mathematical treatment in course of the 17th century. How did the newly realist bent of gaining knowledge of nature the mathematical way affect the ongoing pace of events in the realm of the crafts?

For an answer, I must first stress, as an utterly basic point, that we should *not* indulge our natural temptation to read the resounding successes of science-based technology that are so familiar to us back into those first probings undertaken in Europe prior to the advent of the very mode of science that was to make those successes possible in the first place. Nor should we assume *a priori* that Galilean mathematical science, which indeed was to make so much of the difference on the longer term, necessarily began to make that difference all at once. In fact, my survey of literature in which a variety of crafts in 17th century Europe were examined, has led me to conclude that throughout the Scientific Revolution traditional craftsmanship proved impervious to any prescriptions reaching them from the side of pioneers of the new science. Craftsmanship operating by rule of thumb and, if aimed at innovation, doing so through trial-and-error procedures kept prevailing for a variety of reasons. Mathematical precision was hardly or not at all attained, and if it was indeed this proved practically irrelevant for the time being. The crafts most decisive for everyday life (those responsible for food, clothing, shelter) remained in their traditional, trial-and-error state, whereas, without exception, often quite sophisticated mathematical thinking directed at the solution of more or less pressing practical issues proved as yet wholly impracticable. It does not matter whether we find ourselves dealing with musical temperament, or with the mathematical improvement of windmills used for draining, or with the taming of water streams in the Po delta and the Venetian lagoon, or with efforts to enhance shooting range and improve shooting accuracy the mathematical way, or with estimating and comparing the strength of materials, or with the measurement of geographical longitude on board ship, or with the determination of machine efficacy with which I started my discussion of these matters. For all the sophistication of the mathematical approaches advocated and most often tried out as well over the 17th century, in not one of the various crafts involved did practitioners feel by such efforts called upon to alter their customary ways of proceeding.

How could this be so? By century's end the Scientific Revolution culminated in the universal laws of nature put down in Newton's *Principia* and *Opticks.* How is it that by then the gap between mathematical science and the crafts yawned almost as widely as it had at the onset of the Revolution, about a century earlier?

One principal reason is that, from a contemporary point of view, there was scarcely ground for suspecting at the outset that the gap was so wide in the first place. A marvelous new tool of, in principle, great generality had now become available, the subjection of the empirical world to mathematical rule and order; why should the empirical world of craftsmanship fail smoothly to fall into line? At the time, the issue was not posed in anything like so clear-cut a manner as we can pose it in retrospect. Still, we may regard the Scientific Revolution as marked by a voyage of slowly yet surely advancing discovery that, and why, the gap could not be overcome by jumping over it in one big mathematical leap, but required a good deal of patient, laborious bridge-building.

What bridges, then, and who had to build them, craftsmen or mathematical scientists?

This differed considerably from case to case. Craftsmen's virtually innate conservatism, their aptness to leave things that work intact and to seek solutions for upcoming practical problems in the general direction of what has already proved workable before, is sometimes quite functional, sometimes less so. It is very hard, often impossible, however, to decide in advance when we are dealing with experience-based, sound judgment, when with no less experience-based prejudice. Werckmeister, the church organist, can in retrospect be seen to have done well to ignore mathematical scientists and their tendency to prefer both mathematical and musical elegance over practicality. In contrast, Galileo's analysis of machine efficacy, which likewise went against craftsmen's intuition, and was likewise devoid as yet of possible practical consequences, was in due time to alter craft practice almost beyond recognition. It is hard for us not to sympathize with the predicament of those cardinals who, in the early 1690s in a committee on the river Reno in the Po delta, lacked any objective criteria to choose between the competing claims of Guglielmini, a mathematical scientist in Galileo's wake, and of his Jesuit opponents and their down-to-earth experiential bent in the tradition of the great Renaissance artisans. We cannot but sympathize as well with Huygens' complaint, in a report about the performance of his clocks on the route back from the Indies, how much their overseers had suffered "from the crew's frequent scolding and mockery of this effort to measure longitude in a new way" which, as Huygens rightly foresaw, was in due time to save the lives of so many sailors.[14]

But the survey I have made also leads me to drawing some conclusions valid for all these varied cases.

First, the degree of urgency of the particular practical problem for which mathematics was adduced as a solution made no difference at all for the outcome.

Whether perceived at the time as pressing (notably, water management, and the determination of longitude on board ship) or not (in particular, the efficacy of machines and the strength of materials), none of these problems had even come close to resolution in practice by the century's end.

Demand, then, did not sufficiently foster resolution; but neither did craftsmen's conservative leanings necessarily stand athwart it. In many a case the very initiative came from craftsmen; even if not, when plausible modes of change in a new direction were put forward by mathematical scientists (in perspective, fortress building, navigation, map making), craftsmen ready to go along invariably came forward. From whatever, mostly status-related sources their inclination to stick to trusted procedures might spring in addition to the inherent one already adduced, the more open-minded among them could overcome it; what, then, did prevent such plausible modes from presenting themselves in all other cases?

In retrospect, four impediments to practical success stood in the way of the big mathematical leap:

a. The weightiest impediment of all rested in a serious underestimation of the messiness of the real world. For craft after craft it appeared in course of the Scientific Revolution that, beside determinants taken up indeed in the mathematical model, there were others of at least equal significance, and also many second-order effects, which somehow had to be brought under mathematical rule as well.
b. The mathematization of second-order effects, in particular, required an ability to handle non-uniformly varying magnitudes which the Euclidean doctrine of ratios was inherently incapable of satisfying but was to be yielded by the calculus.
c. Even if using Euclidean means only, craftsmen's ability and/or readiness to grasp the apparently esoteric language of mathematics was very limited. Nor was there as yet sufficient incentive for the drastic educational reform required to make fruitful communication between craftsmen and mathematical scientists a matter of more than just rare good luck.
d. Such communication was further impeded by social distance. Many a mathematical scientist stemmed from the lower or higher nobility or had to adopt its standards in any case, and thus tended to regard the equal footing really required for fruitful exchange as beneath his dignity.

Due to at least these four retrospectively distinguishable barriers, then, the crafts stood to gain very little from those numerous efforts undertaken with a view to their scientific improvement (I mention only in passing that, *vice versa*, mathematical science did benefit greatly from the experiences thus undergone, which in most cases centered around the utterly novel practice of mathematical modeling).

To return to our gap, we do find in course of the century some budding recognition of this state of affairs, as well as some early efforts to overcome it. Galileo and his Italian disciples provided the first recognizable cluster of crafts/mathematics interaction. These few men were greatly inclined to stick to one-sided, mathematical idealization in the sometimes more, sometimes less complacent expectation (fed by their still brand-new conception of the world as inherently mathematical) that experiment would confirm it or, if not, could conveniently be reasoned away. In the second half of the 17th century, in the *Académie Royale des Sciences*, Huygens and Mariotte, in particular, began, also mathematically but in a more open-minded experimental vein, to take the world's messiness into account and to explore second-order regularities. Finally, whereas contemporary concerns of the Royal Society with how to make the new science impinge on craftsmanship took a distinctly empiricist, hence, non-mathematical direction overall, in book II of Newton's *Principia* we begin to discern a first glimpse of what the calculus, once applied to practical issues, might in due time be able to accomplish.

The removal of impediments (a) and (b), thus instructively explored by mathematical scientists in course of the 17th century, was to be pursued with ever increasing zest and refinement over the next, producing one mathematical model after another of sufficient sophistication to become of real practical value. In a few cases mathematical scientists turned themselves into something resembling craftsmen. Most often, however, the emergence in course of the 18th century of craftsmen of a thus far wholly unknown type like Parent or Smeaton was to prove decisive in removing, or at least softening, impediments (c) and (d).

What, in terms of our *Economist* piece, do these conclusions mean? We conclude that its objection (2), about the great pioneers of 17th century science fostering practical application of their work in vain, is by and large sound. Not only does it cover the case of *mathematical-experimental* science well. But more empiricist, definitely non-mathematical yet otherwise similar efforts undertaken in Baconian circles to make their revolutionary, fact-finding experimentalism such as had equally arisen in revolutionary fashion in the 17th century serviceable in practice, display very much the same pattern. I already mentioned in passing Hooke's vain hopes to make the deaf hear again, and Glauber's schemes for turning wood juice into manure. It has further been shown how Hooke's dynamical insights stood in the way of the successful resolution of certain other practical problems he had posed himself and believed he could solve with science (e.g., how to make a lamp burn steadily; or the optimal way to trim sails).[15] And of course I have already broached the case of atmospheric pressure, which I shall now elaborate a little further since, early in the 18th century, it was the very first to undergo a decisive twist.

The story of what eventually (unplanned and unforeseen) became the high pressure steam engine takes its departure in Galileo's becoming aware of craft

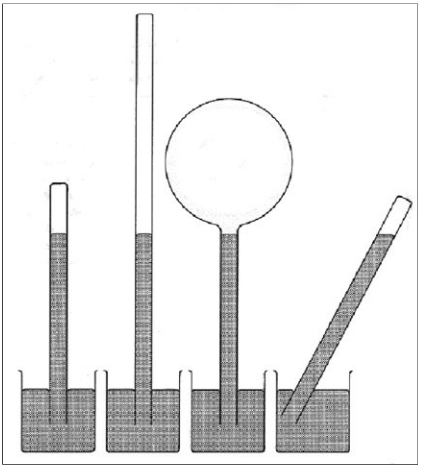

Figure 4: Experiments with Mercury

experiences with the suction pump. The apparent impossibility to pump water to greater heights than c. 10 meters led him to a radically novel, non-philosophical, newly-scientific manner of thinking about the void. Philosophers had treated the void as an issue to be decided *a priori* from first-principles. Galileo rather felt that the matter had to be decided *a posteriori*, by means of mathematical theorizing plus experimental testing. His disciples pursued the issue further using mercury (Fig. 4).

They quickly became persuaded that the space above the mercury in the vessel is void, and that you are dealing with a balance between the mercury column underneath the void space and the column of heavy air that presses upon the surface. Pascal elaborated all this, and confirmed it the experimental way. Von Guericke sought to measure, exploit, and demonstrate in spectacular fashion the pressure exerted by the atmosphere (Fig. 5). Inspired by Guericke, Huygens sketched a design for an engine hopefully capable of the cyclical re-creation of a void space using gun

Figure 5: Guericke's Magdeburger Hemispheres

powder at the bottom of a cylinder. His assistant Papin then replaced gun powder with boiling water and its cyclical condensation. So far events fit the pattern just sketched for both mathematical-experimental and Baconian-experimental science. With Papin's device we have now in hands the theoretical solution to a practical problem, yet the practical solution remains out of sight, thus leaving current craft practice in the draining of mines unaffected. But then there is a decisive twist. The event of the Huguenot Papin crossing the Channel serves as a neat symbol – at that exact point Newcomen took over, turning Papin's theoretical solution into a truly practicable one. It is on the European Continent mostly that 'the theory of practice' was elaborated. But the onset of its actual, practicable realization in course of the 18^{th} century proved, not only with Newcomen but with scores of others in his wake, to be a feat in large measure British. Why?

A British exception

To answer that question, we move a half-century ahead and consider two near-simultaneous yet quite distinct efforts to improve the operation of Newcomen's fire engine, meanwhile at work all over Britain's coal mines for half a century. One effort at improvement was undertaken by James Watt, the other by John Smeaton.[16] The latter was a highly gifted man capable of reaching the outer bounds of what a given line of attack still can yield. Watt was a genius endowed with two rare gifts: he could 'think laterally'; he could saturate himself with a problem largely of his own making, managing in the end to hit upon a solution that looks obvious only in retrospect. But their respective intellectual pre-histories also account for part of the difference. More so than Watt, Smeaton was drenched in the waters of the new science. When out to improve Newcomen's engine, he applied to the job the very model of methodical experimentation. He successively altered one parameter at a time while keeping all others constant, with the result that at the end he had doubled the machine's performance. From our present-day vantage point this is not much of a result – due to Smeaton's efforts, in terms of energy efficacy the net yield increased from c. 0.5 to 1 %. But the proper criterion by which to measure the outcome is in contemporary terms – the net yield of the engine was no less than doubled. Even so this meant that a vast energy loss had marred its performance so far. The one to sense that this was so, was James Watt.

Watt's original job was quite humble. He was asked to repair a 1:5 scale model of the engine, used in Glasgow University for demonstration purposes. In course of the job, which he originally approached "as a mere mechanic", the machine induced in him a sense of wonder, at a far more fundamental level than any attained by Smeaton. What actually happened to what he alone felt to be an outrageous amount of fuel burned away by the machine? Luck had its part, too, in that Watt was the local handyman at the very university where the onset of a science of heat was farthest advanced in the world. Still, what makes Watt unique as an inventor in that intermediate class of what I call 'engineers of a new kind' is that, rather than using pieces of science already available, he single-handedly went ahead and discovered some more himself. But he also realized that, with that much accomplished, he still had to address the ensuing, tough problem of how to make those new scientific insights in 'theoretical practice' serviceable for 'practicable practice' in its turn. This was the harder to do as his own arguments and calculations ended in a paradox – the engine had to be cooled down and kept hot at one and the same time. Here is where Watt's genius revealed itself. He managed to bypass the paradox, and invented the separate condenser. Now the pathway was opened toward ever increasing savings in energy and costs, and also toward turning the engine to uses far beyond emptying mines of water.

At this point, recall two key elements in my preceding analysis of the 17th century gap between mathematical science and the crafts, to wit, the mathematical overshooting of the mark, and the underestimation of the world's messiness. Under the aegis of Francis Bacon, whose message few on the Continent were prepared to take at all seriously, British scholars had turned themselves into masters of the messy, while leaving sophisticated mathematics rather to the Continent. From c. 1700 onward, culturally dominant France served as the locus for expertise in advanced mathematical science. By that time, Britain in its turn had a century of rather haphazard, Baconian experimentation behind it. And this is how Britain could become the expert in precisely the sort of relatively low-level finding and then binding together of scientific facts where the messy problems one encounters when turning 'theoretical practice' into 'practicable practice' were most often situated. This is a crucial point indeed. Jonathan Swift in *Gulliver's Travels* mercilessly satirized the haphazard experimentation that flourished in the Royal Society, in apparently pointless projects like (in Swift's unforgettable example) 'the extraction of sunbeams out of cucumbers'. Less than half a century later it turned out that the tentative, certainly theory-imbued yet comparatively low-level empiricism which Swift had helped make look so ridiculous proved to be the very approach most proper for effectively bridging the gap. For all kinds of reasons Britain also acquired an edge in overcoming impediments (c) and (d), craftsmen education and decreasing social distance. For instance, associations like the Birmingham Lunar Society emerged where entrepreneurs, scientists, and engineers of the new type met regularly and exchanged novelties.

To sum up the present point. We are dealing here, not with British exceptionalism as a broad outlook on history, but rather with a quite specific, truly British exception. Between Newton's death in 1727 and Maxwell's early probings in the 1860s mathematical science was hardly Britain's strong point. In the 18th century it is rather on the Continent that we find men like Parent or Bélidor concerned with the application of mathematical science to practical practice, in direct continuation of work by Huygens and Mariotte. But insofar as the less mathematical sciences are concerned, Britain is where the significant inventions were made. With men like Harrison, Newcomen, Smeaton, Watt, we watch the rise of engineers of a wholly new kind – men to pick up such components of modern science as had come up in 'theoretical practice', and then fruitfully to join these to the greatest gifts of truly inventive craftsmen of the past. That is how Harrison mastered sufficient scientific theory in the domain of metal expansion, and joined it to the kind of single-minded, manual dexterity and inventive genius not even the most practice-minded scientist possessed, so as to find the practicable solution to the problem of longitude solved long before in 'theoretical practice'. That, too, is how Newcomen did what Papin had not done. Papin had proposed to turn the condensation of boiling water in a cylinder and the usage of the consequent rise of the piston for the working stroke – Newcomen turned the idea into a practicable engine. Not counting some success stories of craft/science interaction in a few 17th century scientific instruments, which really are a case apart, Newcomen's 1712 engine was the first large-scale specimen of that world-historically unprecedented phenomenon, the onset of science-based technology.

Back now to our *Economist* piece, and its objection (2) in particular. We may wholeheartedly agree *with* its author that Galileo's or Huygens' or Hooke's science was not as yet up for practical application. But we must also emphasize *against* him that the first significant stirrings of a science-based technology are to be dated, not to Edison's times but 150 years earlier, to the early 18th century. What happened in the 17th century was in effect a learning process, which began to pay off in the 18th, when a new type of engineer learned to combine craft practice of the customary, trial-and-error and rules-of-thumb kind with advanced scientific insights, be these picked up orally or in writing. Of that new type, Thomas Newcomen stands out as a very early, possibly the earliest representative, with men like John Harrison of chronometer fame or John Smeaton, who doubled the fire-engine's effective power, following in his footsteps. The mechanician James Watt then came up with basic scientific insights about heat and steam of his own finding, which led to so drastic a transformation of the fire-engine that henceforth it could serve to power, not just the pumping of mines which under other market conditions might also have been performed by horse- or man-power, but entire production processes. As noted, Watt in so doing brought our new type of engineer to a, once again, novel plane of achievement.

To round off this particular issue in terms of our *Economist* piece, we can now see that its objections (1) and (2) combined, i.e., the objection arising from the gap between the Scientific Revolution and the onset of industrialization, is not really an objection to positing a close causal connection between the two events at all. Rather, it may serve as a stimulus toward a better understanding of how exactly the connection is to be drawn.

A Chinese steam engine?

One gap in the argument remains to be filled. The *Economist* piece strongly implies (and some economic historians affirm without much ado) that at least the basics of what, in the 1760s through 1790s, James Watt wrought out of Thomas Newcomen's first piece of science-based technology might just as well have been pulled off in China. But is this a plausible story line? Even if it were true that knowledge about atmospheric pressure was available in China, we would at best have a necessary, yet certainly not a sufficient condition for a Chinese steam-engine or even a fire-engine. I keep in high regard the heuristic fertility of imagined, alternative pathways taken by humankind beyond the ones actually in past or present. As we do in our everyday lives, so in history too we ought to distinguish at all times between three kinds of events: those that happened, those that failed to happen because they could not possibly have happened, and those that failed to happen even though realistically speaking they might well have happened. For instance, numerous reasons have led me to think that some Galileo-like achievement by the end of the Golden Age of Islamic science is among the alternative pathways that might in principle have been taken. But the case of China is different. A native-Chinese steam-engine belongs rather to my second category of historical events – the (given the state of affairs at that particular time and place) inherently impossible ones. Given the overall tenor of nature-knowledge in China, I cannot possibly imagine what such an alternative pathway might have looked like. In particular, I fail to see how such a piece of machinery might ever have been constructed in the absence of the kind of counter-intuitive knowledge of the void which only incipient modern science in Europe began to provide. What is so special about the fire-engine and, *a fortiori*, the steam-engine is not that in how it works usage is being made of the action of certain scientific principles. So do a celt or a bellows. The discriminating question is *whether the usage was conscious* and, if so, *whether that consciousness was necessarily required*. Take the case of the mixture stops in late medieval organs that I have mentioned before. Here it was quite possible to put to marvelously productive usage scientific principles unknown as such. The effect was attained rather by arranging and subtly cutting up certain kinds of organ pipes in a purely empirical, trial-and-error manner. So, the true question to ask about a possible, alternative pathway for the steam-engine is whether it might have been pulled off with condensation of steam in a vessel and atmospheric pressure being exerted upon the void thus created, without knowing about it. Might have happened with the fire-engine what happened with those mixture stops, i.e., craft construction upon an unknown scientific foundation? My mind boggles at the notion that it might ever have occurred to anyone anywhere to put together, just gropingly, a boiler, a cylinder, a piston, and an assembly fit to ensure regular condensation-cycles in a space regularly drawn void. Maybe it is just my mind that boggles, but at the very least the burden of proof rests upon those who fancy that there is no problem here at all, and that the West owes the prime power mover behind significant stages of its industrialization process to sheer chance. None other than Joseph Needham, in the 'Newcomen Centenary Lecture' he delivered in 1963 for the Newcomen Society under the title 'The Pre-Natal History of the Steam-Engine', took the inconceivability of such a hypothetical occurrence wholly for granted. This is the more significant as Needham rarely if ever forwent a chance to raise a claim for Chinese priority and general excellence in science and technology. In this particular paper he argued no more than that James Watt, both for making his steam-engine double-acting and for converting its to-and-fro motion into rotary motion, may well have made unconscious usage of certain techniques devised first in pre-modern China and then transmitted to Europe along a hypothetical yet (in Needham's reconstruction) plausible route. So that, in his peroration, Needham concluded that

> "no single man was 'the father of the steam-engine'; no single civilisation either [...] Yet no one comes nearer to deserving the title than Thomas Newcomen. In the light of the foregoing analysis he stands out as a typical figure of that modern science and technology which grew up in Europe only, while his successors, great as they were, drew upon older Asian inventions more than has hitherto been recognised."[17]

Modern science and the Western origins of the modern world

We survey now one final time the three objections raised in the *Economist* piece against the idea (which it grants at the outset to be so plausible at first sight) that modern science & technology were highly instrumental in bringing forth our modern world. We conclude that that idea, for all those well-chosen objections against it, keeps expressing a profound historical truth. Yes, science & technology and the relation between them are subtler than is often being thought. Yes, the pioneering period of our modern science is not when our modern, science-based technology came into being. But no, the advent of that modern, science-based technology did not have to await Edison. Yes, there are craft elements in the Industrial Revolution that could do well without modern science or any science at all (notably the first machines for mass spinning and weaving), even though even there modern science quickly became instrumental, too (e.g., in providing the chemicals indispensable for mass bleaching and dyeing). But no, the Industrial Revolution as the event *par excellence* to usher in our modern world cannot even be thought of if a science-based technology, and, hence, the kind of science on which to base such a technology in the first place, had not come into being before. And no, there is no possible way for products of science-based technology to have come into being along any other route than that of modern science as a necessary (though not, indeed, as a by itself sufficient) condition.

These conclusions in their turn raise two further questions of major proportions. Here is not the place to seek to resolve them, but at least they ought to be broached.

The first major question is, simply, What about China? Even if it be granted that the steam engine requires modern science as an indispensable precondition, a good part of my argument were to fall flat after all if it could successfully be argued that our modern science might just as well have emerged in China or in any of the other great pre-modern civilizations, with its actual emergence in 17th century Europe being just a chance event as some economic historians maintain or at least take for granted. It would go far beyond the limits of the present paper to place before the reader my own effort at resolving the compound of questions here involved. Joseph Needham was the first to raise it on the grand scale and to seek a variety of answers to it.[18] The question has subsequently given rise to much debate of a (most often) rather ill-informed kind. Here is a point-by-point *précis* of how I have come to conceive of the issues principally involved.[19]

In the first place, for the only two pre-modern civilizations which experienced sustained bouts of advanced research into the true nature of natural phenomena, the Chinese and the Islamic, things stand mutually quite differently. Nature-knowledge in the Islamic world was like its mostly later, medieval and Renaissance European counterpart insofar as both took their origin in the Greek corpus of nature-knowledge. The question of why modern science eventually arose in the latter, not the former, reduces in my view to the question of how it is that, of two overall rather similar episodes, the Golden Age of Islamic nature-knowledge in the 9th to 11th centuries and the Golden Age of Renaissance nature-knowledge in the late 15th and 16th centuries, the latter was followed by a range of revolutionary transformations whereas the other was not. Modern science rested as an as yet unrecognized, developmental possibility in the Greek corpus of mathematical and natural-philosophical researches. The question is whether that potential was ever to be realized. For that, a 'cultural transplantation', or wholesale migration of the Greek legacy to another environment than the one in which it emerged originally, was indispensable. In particular for mathematical science in the Alexandrian tradition of Euclid and Archimedes and Ptolemy, a Galileo-like development was not ruled out beforehand on grounds of its content alone. Why that development did take place in Europe, not in the Islamic world, has less to do with some purportedly essential character of either of these civilizations or with any given characteristic of the monotheistic faith reigning in either than with the historical incident of vast waves of military invasion. Around 1050, near-coincident with the very Golden Age of Islamic science, one nomadic horde after another began to trample underfoot the fine ramifications of the civilization in which that science was fostered, in contrast with Europe, which then and later was spared such wanton destruction.

With China not the developmental possibilities of the Greek way of dealing with natural phenomena form the crucial point, but rather the developmental potential of an indigenous approach to nature profoundly different from the Greek. In the Chinese conception, which likewise began to be developed in the 6th/5th centuries BC, what coherence was supposed to underlie the endless variety of phenomena resided in their mutual dependence.

> "The regularity of natural processes is conceived of, not as a government of law, but of mutual adaptations to community life […] [The way of the Chinese was] to systematize the universe of things and events into a structural pattern which conditioned all the mutual influences of its different parts […] For the ancient Chinese, things were connected rather than caused […] The universe is a vast organism, with now one component, now another, taking the lead at any one time, with all the parts co-operating in a mutual service which is perfect freedom.
> In such a system as this, causality is not like a chain of events […] The concept of causality where the idea of succession was subordinated to that of interdependence dominated Chinese thinking."[20]

The world, in this conception, is an infinitely subtle fabric. Each thread, however tiny, is interwoven with every other. The nature of the fabric can be grasped by means of correlations, so as to get at the various ways in which the mutual coherence of all things makes itself felt in some given phenomenon. Concepts to exemplify and express this correlative way of thinking are *tao* (the Way), *ch'i* (matter/energy), *wu-hsing* (the five phases), and *yin-yang*. Together, they form the core of what would eventually be turned into *the* Chinese view of the world.

It shall forever remain a moot question whether the corpus of nature-knowledge to be constructed out of this correlative conception of things might in due time have given rise to the core of modern science, the way modern science was in the end to be grafted upon the Greek corpus. On the one hand, the Chinese approach was marked by an intuitive plausibility and an observational streak far removed from core features of modern science – those counterintuitive mathematical features insisted upon in the above. On the other hand, the link with practice in general and with advanced craftsmanship in particular was far closer in China than in pre-modern Europe, as for instance with Shen Kua's 11th century theorizing about magnetism and his invention of something like the compass. In my view the decisive reason for why no revolutionary transformation in the general direction of modern science ever took place in Chinese civilization rests in the circumstance that, unlike with Graeco-Roman civilization, its Chinese counterpart managed over the centuries to survive fundamentally unscathed every single effort to subdue, let alone destroy it. Even in the two cases of outside conquest (Mongol and Manchu) rapid sinification left the fundamental integrity of Chinese civilization intact. As a consequence, such chances for refreshment of a more or less radical kind as the Greek corpus repeatedly received (once in the Islamic world, twice in Europe) did not come up for the Chinese view of the world such as it had taken shape under the Han. Once established, it kept being expanded and made ever more intricate to be sure, yet without an occasion ever arising for the correlative conception of things to be subjected to scrutiny of a fundamental kind and for the outer bounds of that conception to be explored or perhaps even trespassed. In short, if something like the Scientific Revolution were to happen at all, it was to be as a consequence of cultural transplantation of the Greek corpus, not of any other kind of event.

There is, finally, another, quite major question that in the present paper can only be outlined, not answered. What is it that turned Watt's steam engine from a small-scale invention into a real-life machine and, from there, into an immensely productive one? I have argued that by mid-18th century Europe had arrived at the brink of a viable technology erected on occasion upon a previously unheard-of, scientific basis. For all this to usher in the onset of industrialization, however, something more was of course indispensably required – the economic opportunity that actually presented itself in late 18th century Britain in the guise of a readiness to *invest* in such technological novelties as presented themselves. An in many respects independent chain of argument serves to explain the emergence of that economic opportunity leading to those investments and the productive success thereof. The historical question that continues to baffle me more than any other, then, is this: How, in its turn, to explain this *confluence* of two not fully yet by and large independent streams of historical events? Why should the retrospectively required mode of science *and* the retrospectively required need-*cum*-readiness for large-scale investment be there at just the same place at just the same time? There are answers to that question of questions, too,[21] but not ones that still fit in the frame of the issue here addressed of the onset of a science-based technology neither with Edison nor in China or elsewhere, but in 18th century Britain as the outcome of a major learning process instigated by the Europe-wide Scientific Revolution of the 17th century.

Notes and References

1 The Economist, December 31st 1999, vol. 353, no. 8151, 10–12. The cover offers for dates 'January 1st 1000 – December 31st 1999'. It carries two slogans: 'Millennium special edition' and 'Reporting on a thousand years'. The piece may readily be consulted at http://www.economist.com/diversions/millennium/displayStory.cfm?Story_ID=346598.

2 H.F. Cohen, The Scientific Revolution. A Historiographical Inquiry, Chicago 1994, 13.

3 Problems (1)–(4) form the subject of a completed book provisionally entitled 'How Modern Science Came Into the World. A Comparative History'. I have treated problem (5) in an article in Dutch entitled Het ontstaan van onze moderne wereld: wat natuurwetenschap en techniek ermee van doen hadden, in: Theoretische Geschiedenis vol. 25, issue 4, 1998, 322–349.

4 The explanation of the action of Newcomen's fire engine that follows here owes most to D.S.L. Cardwell, Turning Points in Western Technology, New York 1972, 66–72 (also idem, The Fontana History of Technology, London 1994, 121–125). Much detail about the snap action of the valves and cocks and about a whole range of later varieties of the engine is provided in L.T.C. Rolt and J.S. Allen, The Steam Engine of Thomas Newcomen, Hartington 1977.

5 Engraving by Henry Beighton, 1717.

6 Reproduced from J. Needham, Clerks and Craftsmen in China and the West. Lectures and Addresses on the History of Science and Technology. Cambridge 1970, 211.

7 Reproduced from R.J. Law, The Steam Engine. A Brief History of the Reciprocating Engine, London 1965, 8.

8 The indispensability of the Scientific Revolution for some key events and developments that went into the making of the Industrial Revolution has been defended previously in rather different ways by A.E. Musson and Eric Robinson, Science and Technology in the Industrial Revolution, Manchester 1969, and by Margaret C. Jacob, Scientific Culture and the Making of the Industrial West, Oxford 1997.

9 The expression alludes to A.R. Hall's paper The Scholar and the Craftsman in the Scientific Revolution, in: M. Clagett, ed., Critical Problems in the History of Science. Proceedings of the Institute for the History of Science at the University of Wisconsin, September 1–11, 1957, Madison 1959, 3–23. Together with many another contribution to the debate about science and the crafts during the Scientific Revolution, I have discussed it in my The Scientific Revolution. A Historiographical Inquiry, Chicago 1994 § 3.4.3.

10 The section that follows is taken almost fully from my book-in-progress mentioned in note 3.

11 L. Reti made this point in his contribution to the lemma Leonardo da Vinci in the Dictionary of Scientific Biography, vol. 8, 206–214.

12 D.S.L. Cardwell, Turning Points in Western Technology. A Study of Technology, Science and History, New York 1972, 42–43.

13 Ibid., p. 38–39, and idem, Fontana History of Technology, 87.

14 Christiaan Huygens, Oeuvres Complètes 9, 272–291; 289 (report, in Dutch, to the Dutch East India Company of 1688).

15 R.S. Westfall, Robert Hooke, Mechanical Technology, and Scientific Investigation, In: J.G. Burke, ed., The Uses of Science in the Age of Newton, Berkeley 1983, 85–110.

16 D.S.L. Cardwell, Turning Points, 83–89; also enlightening on the 'science' portions in Watt's accomplishment is Arthur L. Donovan, Toward a Social History of Technological Ideas: Joseph Black, James Watt, and the Separate Condenser', in: G. Bugliarello and D.B. Doner, eds., The History and Philosophy of Technology, Urbana and Chicago 1979, 19–30.

17 Joseph Needham, Clerks and Craftsmen, 136–202; quotation on p. 202.

18 I have made an inventory of the numerous and varied ways in which Needham phrased and answered the question in chapter 6 of my book cited in note 2, and also in an article Joseph Needham's Grand Question, and How to Make It Productive For Our Understanding of the Scientific Revolution, in: A. Arrault and C. Jami, eds., Science and Technology in East Asia, vol. 9: The Legacy of Joseph Needham, Turnhout 2001, 21–31.

19 In my book-in-progress mentioned in note 3. I read neither Arabic nor Persian or Chinese, and in the absence of accessible surveys of the history of science in either the Islamic world or China I have had to cull data and sensible interpretations from a large variety of highly disparate resources.

20 In the abridged version of Needham's multi-volume Science and Civilisation in China prepared under his supervision by C.A. Ronan: The Shorter Science and Civilisation in China, vol. 1, Cambridge 1978, 165; 167–168.

21 For example in work by Margaret C. Jacob, and also in J. Uglow, The Lunar Men. The Friends Who Made the Future, London 2002.