Scientific Culture and the Origins of the First Industrial Revolution

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Resumo

O artigo analisa o papel da cultura científica na primeira revolução industrial baseado em uma pesquisa feita na Grã-Bretanha, França e Países Baixos. O seu argumento enfatiza a base do conhecimento acessível aos primeiros empresários industriais e engenheiros, uma base que casa conceitos e aplicações que se aproximam do que hoje é conhecido como engenharia. Esta era a ciência praticada na época, base da tradição newtoniana desde Desaguliers até Dalton. O argumento conta com fontes publicadas e manuscritas de Birmingham, Manchester e Leeds. O autor disputa o modelo de "curioso semiliterário" da primeira atividade industrial em tecnologia de força e suporta argumentos atuais da História Econômica, como os de Joel Mokyr, quem tem se baseado em trabalhos anteriores por esta autora.

Abstract

The article addresses the role of scientific culture in the first Industrial Revolution and is based upon research undertaken in Britain, France and The Low Countries. It summarizes an argument that lays emphasis upon the knowledge base available to early industrial entrepreneurs and engineers, a base that married concepts and applications in ways that were close to what we now call engineering. It was the science practised in the day, basic to the Newtonian tradition from Desaguliers to Dalton. The argument draws on published as well as manuscript sources from Birmingham, Manchester and Leeds. The author disputes the "semi-literate tinkerer" model of early industrial activity in power technology and endorses arguments now being made by economic historians such as Joel Mokyr who have also relied upon earlier published work by this author.

When we think about culture in relationship to economic development obviously most historians turn to science and technology as the key elements they wish to better understand. Commonly we think that we know what is meant by the terms, "science" and "technology." Therein lies the difficulty, at least when it comes to understanding their place in the earliest signs of industrial activity, in the application of power technology to the manufacturing process. Because we do not have a textured understanding of scientific practices late in the eighteenth century we miss their relevance to early industrial developments. My task here is to characterize those specifically British practices, the close interface between science and technology at that time, and to relate them to the origins of the first Industrial Revolution. Finally I want to meditate briefly on the place and uses we should assign to the cultural argument.

Most practitioners of what we today would confidently describe as engineering saw themselves as "men of science" or as natural philosophers

The content and style of both science and technology in eighteenth century Britain differed markedly from what we may recognize in the present, and not least, their interrelationship also varied considerably from what we think of today. When looking at the critically important eighteenth century we are also looking at the moment when civil engineering was being invented as a distinct discipline. Most practitioners of what we today would confidently describe as engineering - James Watt, John Smeaton, William Jessop for example - saw themselves as "men of science" or as natural philosophers. They were skilled within the Newtonian educational tradition that became the dominant paradigm for both mechanics and dynamics by 1720 in Britain (by the 1750s in France). Central to Newtonian practices, application belonged to the curriculum from the 1690s onward.

In Newtonian textbook after textbook, in lecture and demonstration - from Francis Hauksbee and Jean Desaguliers in Newton's lifetime (d. 1727) to John Dalton lecturing in Manchester in 1818 - the subjects tackled began with atomic theory, the relationship between matter and motion, the nature and meaning of the vacuum, and then proceeded by the use of levers, weights and pulleys to illustrate Newton's three laws, then to explicate mechanics, hydrostatics, hydrodynamics, the nature of steam and the working of machines in general. As early as 1705 experimental demonstrators advertised events where instruments were used "to prove the Weight and Elasticity of the Air, its Pressure or Gravitation of Fluids upon each other: Also the new Doctrine of Lights and Colours, and several other matters relating to the same Subjects."[1] *Techne* and *scientia* - while not one and the same thing - were close, indeed inseparable in this tradition. In the 1730s John Grundy, a land-surveyor and teacher of mathematics, proposed that every engineer should "understand Natural Philosophy in order to make his Enquiries just."[2] Shortly thereafter, Desaguliers declared in his published *Course of Experimental Philosophy* that natural philosophers were actually the only realistic guardians to prevent investors from being "impos'd upon by Engine-makers, that pretend to (and often fancy they can) by some new invented Engine out-do all others."[3]

These eighteenth-century practitioners fashioned a distinctive scientific culture that effected a union between theory and practice. The Newtonian style as it emerged

[1] Daily Courant, *Thursday, 11 January 1705, advertising the lectures and demonstrations of James Hodgson; cited in Stewart* (2004, p. 238).

[2] *John Grundy, sr,* Chester Navigation consider'd (*n.d., ca. 1736*). *I owe this reference to Larry Stewart.*

[3] *Desaguliers, 1745, p. 70, 138.*

first in Britain can best be understood comparatively, when seen (as we will shortly) in relationship to how and what was being taught in science and technology at the same time, for example, in France. When being comparative it helps to walk the multi-lingual terrain with the cultural agents, with scientific practitioners and industrial entrepreneurs. When trying to understand what all of this might have had to do with economic change of an industrial kind, it helps to know what contemporaries said about what needed to be done, about how best to use the science of the day to accomplish profit and growth.

Being comparative now in a global age suggests that both the East and the West should be invoked. Thus Kenneth Pomeranz in his magisterial *The Great Divergence* (2000) tells us that while steam engines were important in the British Industrial Revolution, the Chinese had them too. They knew about atmospheric pressure and - witness their box-bellows - "had mastered a piston/cylinder system much like Watt's." In his account China becomes as likely a site "for a series of linked developments in coal and steam central to the Industrial Revolution" as was Britain.[4]

Perhaps without realizing it, Pomeranz displays an understanding of technology that sees it as tacit knowledge, the work of trial and error, brilliant tinkering if you like, thus a set of practices largely divorced from a knowledge base. This view is shared by some historians of technology (for example, Ferguson, *Engineering and the Mind's Eye*, 1992.) Unfortunately the tinkering motif - imaging semi-skilled craftsmen without any scientific knowledge - is encumbered by our contemporary division of academic labor between the history of science and history of technology. The tinkering model just does not reflect the scientific culture at work in northern and western Europe throughout much of the early modern period.

The tinkering school in the history of technology would have the execution of machinery be more a matter of practice than of thought. But that is a false dichotomy, at least for the eighteenth and early nineteenth centuries in Britain. In that world, to use our presentist categories, "technologists" were communicating with "non-technologists," many of them men of science.[5] In other words I am arguing that in their "human built world," to borrow a phrase from Thomas Hughes, creativity and the ability to "read" the machine depended upon a set of shared skills and a knowledge base that industrial entrepreneurs, however technical their manufacturing applications, could own and utilize (in different ways to be sure), along with their scientific cousins (even ones safely armchaired in London).[6]

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While I know nothing about Chinese history I do know that having bellows is very different from knowing that the atmosphere exerts measurable pressure, and it is different from understanding the relationship between the vacuum and pressure, giving it mathematical expression, and not least, knowing how to apply trigonometry to measuring the depth of a body of water. All those skills were possessed by someone like James Watt, from any perspective a key player in early British industrialization. When in 1796 Watt wrote out a list of what a steam

[4] *Pomeranz, 2000, p. 62.*
[5] *Here I am somewhat simplifying the approach found in the otherwise wonderful essay by Lubar (1995, p. S53-81). The word "scientist" only became common in the 1830s.*
[6] *Hughes, 2004.*

engineer needed to know, it began with "the Laws of mechanics as a science," the "laws of hydraulics and hydrostatics," and ended with "the doctrine of heat and cold."[7]

Let me give another example of what I mean by the distinctive interface between science and technology found in the period after 1750. Take the Great Exhibition held in London in 1851. Its process of assessing machinery and reassembling it can be used specifically to discover how science and technology interacted in the presentation and understanding of industrial equipment.[8] Dismantled, the machines were sent by industrialists to London, and reassembled for display by a committee of gentlemen, the majority of whom were Fellows of the Royal Society. Those who would sharply separate science from technology might find odd the role played by FRS committee members. But given what we now know about the scientific culture at work in the entrepreneurial lives of those who sent the equipment, most of them would have found nothing odd about the interaction between gentleman fellows and manufacturers.

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At the London exhibition it might be said that we find "pure technology" removed from its social and economic setting. None of those who reassembled it were inventors, many had probably never been on a factory floor. To be sure, they had help from drawings sent along, and sometimes they had to write back to the entrepreneurs for guidance. Indeed the entire purpose of this exhibition of unprecedented size was to show the world the depth and breadth of British industrial development. It also aimed to "exhibit the beautiful results which have been derived from the study of science."[9] At its execution the exhibition was to display the achievements of science which "discovers the laws of power, motion, and transformation." Also on display was how "industry applies [the achievements of science] to the raw matter which the earth yields us in abundance."[10] Industrialists sent their machines with descriptions, and their actual working had to be replicated on the floor of the exhibition as well as clearly explained in the three volume massive catalogue that accompanied the show. "The occasion called for a large amount of peculiar knowledge - knowledge not to be gained by study, but taught by industrial experience, in addition to that higher knowledge, the teaching of natural and experimental philosophy."[11] The marriage between science and industry conceived by Bacon, put into practice by the scientific lecturers of the eighteenth century, was actualized in the factories of men like Watt and Boulton in Birmingham, or M'Connel and Kennedy in Manchester, or the Marshalls and Gotts in Leeds.[12] Had become the basis of a credo: the union of hand and head make innovation possible.

The catalogue's proofs and the text itself were written and corrected by a

[7] *Robinson and Musson, 1969, p. 204-205 (which prints the manuscript entitled, "Points necessary to be known by a steam engineer", 1796). See also Birmingham City Library, James Watt Papers, MS 3/69, where the young Watt is using trigonometry to try to estimate the volume of Lough Ness. A similar portrait of Watt appears in Marsden and Smith (2005, chapter two).*

[8] *See Jacob and Stewart (2004, chapter five). See also, "The associations of intellect and of technique were more widespread in 1851 than often thought, and acted as a solid base to the Great Exhibition of that year and to the subsequent twenty years of Golden Age machinofacture". From Ian Inkster, found in his edited volume, with Colin Griffin et al. (2000, p. 171).*

[9] *The Art..., 1851, p. I.*

[10] *Ibid., p. 4.*

[11] *Ibid., p. 85.*

[12] *Jacob and Reid, 2001, p. 283-304; translated as "Culture et culture technique des premiers fabricants de coton de Manchester" (JACOB; REID, 2003, p. 133-155). And see the forthcoming, "Mechanical Science on the Factory Floor: The Industrial Revolution in Leeds" (JACOB, 2007).*

committee of "scientific gentlemen." In some cases the pages went back to the owners of the equipment to make sure that the gentlemen had gotten it right. The spirit of Bacon and Robert Boyle was invoked: the need for the natural philosopher to have insight into the trades. The committee made "an attempt...to convert the changing and inaccurate conventional terms of trade into the precise and enduring expressions of science."[13] Clearly the interface between science and manufacturing was sufficiently close in the mid-nineteenth century that the scientifically educated, and presumably innovative, could understand industrial devices enough to explain them to the general public. The Exhibition proclaimed: Science works, and combined with the experience that only hands-on labor could give, both made an Industrial Revolution happen. In 1851 the exhibition suggested that the British way of local initiatives and dedication to practical science would forever trump all competitors.

But that was in 1851. What would scientifically cultured industrialists and entrepreneurs have said in 1780? Let us look at what they thought to be critically important for success. In 1784 Watt told a friend whose son wanted to have an industrial career that he needed to know drawing, geometry, algebra, arithmetic and the elements of mechanics. When Watt directed the education of his own son he insisted upon geometry, algebra, "the science of calculation," physics, mechanics, natural philosophy in general, and bookkeeping.[14] Twenty years earlier when Watt first started his work to improve the steam engine consistently he spoke about his scientific method, his "experiments," about their cost and how they were part of "my education."[15] He regularly copied out experiments done by Priestley and La Place into notebooks where he recorded his own experiments on heat.[16] Experiments on engines at particular cotton mills were also recorded in the same manner.[17] But we might be tempted to think that Watt was one of a kind.

Acumen in scientific culture was not confined solely to industrialists. At the House of Lords in the 1790s engineers had to justify the digging of new canals through private land. The minutes of the committees reveal that peers of the realm understood enough hydrostatics and hydrodynamics so as to query engineers intensely.[18] To be sure some makers of jennies and spindles were semi-literate, more visual than verbal, but by and large, the creators, installers and users of steam and hydraulic presses, the planners and builders of canals - the key players in the British Industrial Revolution - were mechanically literate and in possession of a distinctive cultural persona. When the leaders of Bristol wanted to restructure its harbor they interviewed the best engineers in the land. They

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[12] *The Art..., 1851, p. 86-87. For the long-standing interest of the Royal Society in steam see Smith (1991-92, p. 229-30).*

[14] *Birmingham City Library, James Watt Papers (hereafter JWP), 6/46, Letter Book, 30 May 1784. By that date his firm alone had installed over 27 engines in Britain. Watt understood the relationship between his science and his industrial success; see same collection, MS3/18, letter of 16 Feb. 1782 Watt to Boulton, "I am certain that with proper loads such an engine can easily make 30 strokes per minute when not impeded by vis inertia or gravity". On his son's education see JWP, Letter Book/1 to James Watt, jr, all the letters from the spring of 1785. Note that the JWP only came into the public domain in the mid-1990s and the papers enable us to know much more about Watt's education, knowledge base and values.*

[15] *JWP 4/59 letters of 1768-1775 (when his patent is secured) to Dr. William Small.*

[16] *JWP, C3/10 1782-1812, a thick folio notebook bound in vellum, with notes on printed works as well as on his own experiments.*

[17] *JWP, C4/D31, 1793-95, on experiments over a two year period at Salford cotton mill with his engine.*

[18] *See Jacob (1988, p. 238-243).*

wanted to know the "principles on which the calculations are founded." William Jessop confessed that as a practical man, like most others, he had forgotten much of his mechanics, and would get back to them in detail. But he enclosed a quick lesson in Galilean or Newtonian laws concerning how by experiment "a heavy body falling from rest will descend about 16 feet in a second of time; and that the velocity acquired...would carry it on in equal time through a sphere of double the height which it fell from, or 32 feet in a second."[19]

By the 1780s the choices about power technology and its application being made by entrepreneurs required a specific knowledge and skill base that can be seen in place in Britain, but not yet so clearly - as comparative work has revealed - in France or Belgium.[20] At precisely the same moment Émile Oberkampf, the leading cotton industrialist of Rouen, left a set of instructions for his son about what he needed to know to succeed in their business. There is absolutely no mention of mathematics or mechanics.[21] Had the Oberkampfs been forced to emigrate in the 1790s they would have had a hard time making a go of it in Manchester. In 1782 Watt criticized one of his competitors in a letter to Boulton, "as his theories are all abstract and run only on the commonly known properties of steam as an elastic fluid I cannot conceive anything wherein he can surpass us particularly as he seems to be greatly divested of geometrical principles."[22] Theories alone would not do the necessary work, and more than arithmetic was also needed. Yet it was also seen to be true by Watt's contemporary, the engineer Robert Beighton, that "the affairs of the world could never be carried forward without the help of Science."[23]

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Take the example of the leading linen manufacturer in Leeds by 1800. When John Marshall experimented with his equipment in order to improve its efficiency he did so with mathematical precision and with reference to general laws.[24] He was also a consummate technologist, intensely interested in machines employed by others or in other industries, such as those used in cotton spinning.[25] With his own machinery friction was a matter of particular concern. This quotation from one of his experiment books dated 1795 demonstrates how calculation and generalization figured noticeably in his scientific and technological style:

> The teeth of two wheels working together must necessarily rub against one another over so much space as the difference of length of two radii meeting at the center of action of the two wheels & of two radii meeting at the thickness of a tooth from the center of action, which is the place where the teeth first begin to act. Consequently the finer the pitch & the less friction there will be upon the teeth. The best form of the teeth of wheels is that which is the strongest & at the same time admits no

[19] Bristol Record Office, Bright MSS, 11168(3), 15 Nov. 1790, Jessop to Bright.
[20] For the comparison see Jacob (1997, chapter seven).
[21] Archives nationales, Paris, 44 AQ 1 (93 M 1), "Regles generales pour la conduite du commerçant". Hereafter the archives are referenced as AN.
[22] Birmingham City Library, JWP, MS3/18, 9 February 1782.
[23] West Yorkshire Archive Service, Wakefield, MS C482/1 19 June 1778, Beighton writing to William Martin, also with a discussion of Priestley's views.
[24] The Brotherton Library, Leeds University, Marshall MS 200/57 Notebook c. 1790, f. 38 labeled Strength of wheels, "To find the strength necessary for any given power - Rule The square of the thickness....".
[25] Ibid., f. 17 labeled Speed "the greatest speed at which they can spin cotton is 15ft a min. or 12 feet a min the day through including stoppages."

tooth to come into contact but that which is in action.[26]

Similarly the action of the bobbins as they spun the linen was approached mechanically: "the relative length & diameter of a bobbin must be so proportioned that it will always be the same weight in proportion to the lever at which the thread is acting."[27] The Marshall family, like their neighbors the Gotts, were well versed in the science of their day and they saw its application to the manufacturing process.

The French case

By the 1780s foreign observers began to realize that in Britain theory and skill were interconnected. At that moment a French industrial spy in Watt's circle, as Watt told Joseph Black, was making "many enquiries about your latent heat."[28] For several decades French ministers of the interior had evinced a growing interest in British technology, an interest that became an obsession by the 1780s. After 1789 and in the wake of revolution the new French makers of educational policy sought to put in place their vision of how science and technology should interface. It was explicitly modeled on what French observers believed to be the nature of scientific culture in Britain, and what the preponderance of applied science meant for industrial development.

The Napoleonic wars exacerbated the French instinct to compete in market place, factory and classroom. Posters went up in the provinces: Artistes et mécaniciens de la Gironde!--search for machines that will replace the hand![29] As historians of France have put it, "about the turn of the century and on into the early nineteenth century, it became increasingly common for some kind of training in science, in particular in chemistry or the scientific aspects of medicine, to be seen as a natural prelude to entrepreneurial activity."[30] This cultural assumption about the usefulness of science to entrepreneurs had become a commonplace in Britain.[31] Around 1820 as the French were obsessively counting all the steam engines in the country, they discovered that the overwhelming majority were still imported from Britain. The best scientific minds of the day lectured their readers on the necessity for steam engines, and the government, as well as local societies, awarded prizes for the innovative engines made in France.[32] Also in the provinces new societies were established to study systematically agriculture as well as cotton production - and the weather.[33] Their informal ambience and applied concerns remind the present-day reader of minutes from the literary and philosophical societies at work across the Channel in places like Manchester. Many began in the eighteenth

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[26] *Marshall MS 500/57, Notebook c. 1790, ff. 24-25. See similar points being made by Vince (1793, p. 40).*

[27] *Marshall MS 200/57, ff. 34-35. Note, in lectures remarkably similar to Booth's, the following appears in the first lecture: "If any two weights balance each other when hung from a straight lever, they will be to each other inversely as their distances from the fulcrum". Found in Rev. S.Vince (1793, p. 7). These lectures concerned and in this order: Mechanics, hydrostatics, optics, magnetism, and astronomy.*

[28] *JWP, Letter Book, w/5, Watt to Black, no date but from the order, probably 1780. On this circle see the illuminating work of Levere and Turner (2002); see also Jacob and Stewart (2004).*

[29] *AN F 12 2204, Dubois, "Le Conseiller d'état, Préfect du Département de la Gironde à ses Concitoyens, Fructidor Year IX".*

[30] *Fox and Guagnini, 1999, p. 14. For a prize to reward such innovation in applied science, established in the year 8 in Lyon, see AN, F 12 2359.*

[31] *AN F 12 2200, Fauchat,* État des machines à vapeur importées d' Angleterre en France depuis 1816, *dated April 7, 1819. For an overview of French industry in the period see Béaur et al. (1997).*

[32] Bulletin de la Société d'Encouragement pour l'Industrie nationale, *a report by Prony dated 13 September 1809 and found in AN F12 2200.*

century, but after 1800 fine literature faded from their proceedings, to be replaced by discussions of land cultivation and industrial development. In keeping with the centralization of education, the French societies, unlike their British counterparts, were also charged with finding appropriate students for the new technical schools.[34]

When the French invaded the Low Countries in 1795 a similar effort at industrial development occurred around Brussels and it too was dependent on cotton spinning machines imported from England.[35] The professor of mathematics at Liège in French-controlled Belgium taught calculus and trigonometry but also devoted two months to lessons on terrain and the measurement of elevation for use in maps, while his colleague, also in mathematics, taught arithmetic "relative to commerce and to mathematics, the new system of weights and measures," and decimalization. In nearby Ghent the professor of chemistry and experimental physics turned the second year of the course in a decidedly applied direction and taught about the properties of water, about thermometers, optics, theory of colors, etc. He then paid considerable attention to the metals that appear in mines, the extraction of minerals, the use of specific gravity to identify substances, and to an examination of the principal substances found in the region. He also gave a course particularly for commercial students.[36] By 1820 Ghent held an industrial exposition at which its metal industries figured prominently. Because of its cotton industry, Ghent had become known as "Manchester on the Continent."[37] From recent studies of developing regions and nations we now know that the French promoters of industry back in the 1790s had it right: education and knowledge make a difference.[38] Then, however, the French had reason to be worried. Without any of the social scientific evidence we now possess, they turned to the scientific content of their educational curriculum to push it in a more applied direction and thereby to enhance international competitiveness.

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Historians a generation ago saw the new French educational system put in place after 1795 - and changed and augmented repeatedly - as an attempt to separate the classes, to keep workers in their place and an "affirmation of the role of the industrial bourgeoisie."[39] To be sure elements of class dominance were present, yet so too was a new democratic turn. In 1795 the écoles centrales had been a democratic experiment that brought general and technical education to a lower level of society where it had never been seen before. In the conservative reaction under Napoleon that experiment was abandoned, and the new, more elite lycees replaced the schools. They were meant to favor the sons of military and civil servants as well as serve the industrial needs of the state. Yet

[33] *Bibliothèque de la ville de Lyon, MS 5530, la Société libre d'Agriculture, histoire Naturelle & Arts utiles de Lyon; the range of the society was both agricultural and industrial, commencing in the year 6.*

[34] *Archives nationales, ADVIII 29, "Classification des places d'Elèves....".*

[35] *AN, F 12, 533, Ministry of the Interior, "Rapport à Sa Majesté l'Empereur et Roi...", November 23, 1808.*

[36] *The printed* Programme des cours de L'École Centrale du département de l'Escaut, qui s'ouvriront le primier brumaire an XII, *Ghent, 1802, pp. 6-7, and found in AN F17 1344 14.*

[37] *Rijsarchief Gent, Hollands Fonds, inv. nr 611/2 for details on the exposition.*

[38] *Jones, 2001, p. 57-79.*

[39] *Léon, 1970, p. 846-847.*

very bright students would have their way paid, regardless of what their fathers did for a living. The sites chosen outside Paris - it would get three of the new schools - were all places where industrial activity already existed.[40]

Rather than seeing the French partnership between industry and the state as a means of social engineering that favored one class over another, it might better be understood as a somewhat desperate attempt to set up a new innovative class, a scientifically literate meritocracy with entrepreneurial skills that would create the needed institutions. In addition to creating a new nation of republican citizens, and then after the reaction of 1815, a new nation of citizens loyal to their king, the French educational system set out to create a national, rather than regional or local, culture receptive to industrial development. The kind of people to be found readily in Manchester must now be created - seemingly out of whole cloth - but from among the children of state functionaries or the exceptionally bright. Report after report focused on the equipment needed in these schools, models of machines, chemicals for experiments, new laboratories, the best textbooks.

In Lille, an area already with industrial activity, the local college stressed the need in science to blend theory with practice.[41] In the same town a free course in physics was established by the municipality but encouraged by the national ministry, and in the local secondary school the professors of letters and physics, as well as design, were paid an equivalent salary.[42] In the new post-1795 school English was also to be taught because it was increasingly the language of commerce.[43] Making good citizens meant in Lille also forming workers who understood the chemical processes in dying and the development of textiles in general.[44] State inspectors railed against the mediocrity of instruction in mathematics and decreed that

[40] *Archives nationales, Roederer MSS 29 AP 75, f.393 a lycee for 150 would have 9 professors and 3 administrators; f. 397 every district to set up its own primary school; directive of 5 April 1802 (f.399) said that mathematics was to be taught in secondary schools.*

[41] *Archives departementales du Nord (hereafter AD), IT 407, (printed brochure from 1820) Université de France, Collège Royal de Douai, "Les objets de l'enseignement sont: la religion, les langues anciennes et modernes, les belles-lettres, la philosophie, les mathématiques, la physique, la chimie, l'histoire, la géographie, l'écriture, le dessin. Il y a un cours spéciale d'Anglais, dont le professeur est payé comme cexu des cours précédens, par le Collège, et un cours d'Allemand, dont le Professeur reçoit le rétribution des élèves qui le suivre…Les élèves sont initiés à toutes les connaissances littéraires et scientifiques, indispensables pour être admis à l'école polytechnique, ou à toute autre école spéciale. Outre les treize Professeurs chargés d'enseignement, il y a un maître d'étude, ou répétiteur, par vingt-cinq élèves, chargé de les aider dans leurs études, de surveiller leur travail et de faciliter leurs progrès. Il y a un cabinet de physique, riche en instrumens, et un laboratoire de chimie bien organisé, pour que les élèves puissent, dans les sciences naturelles, joindre la pratique à la théorie. Ces ressources sont d'autant plus utiles, qu'une ordonnance royale prescrit que les candidats au baccalauréat seront examinés sur tous les objets de l'enseignement donné dans les Colléges Royaux et y comprix les mathématiques et la physique. Les élèves qui désirent prendre la grade de Bachelier, sont particulièrement exercés….".*

[42] *AD, MS IT 19/1, Facultés des sciences/Cours de physique à Lille, 1817-1852. Ministre de l'Intérieur L'Etablissement d'un Cours de physique expérimentale à Lille est approuvé Paris, le 15 8 bre 1817. For salary see MS1T 30/1.*

[43] *AD du Nord, MS L 4841 from the year 8.*

[44] *AD du Nord, L 4842, and from the same period, "Il seroit difficile de ne pas sentir l'avantage d'un plan d'éducation aussi vaste et ainsi coordonné; il n'est presque pas un art, pas une profession utile et honorable, dont les connoissances spéciales ne dérivent de quelques-unes des sciences dont on vient de tracer le tableau: il sera aisé d'appercevoir que le cours de dessein, réuni aux cours de mathématiques et de physique, renferme tous les élémens de l'art de l'ingénieur, tant civil que militaire; d'artilleur, d'architecte (les jeunes gens qui se seront distingués dans ces sciences, ont la perspective d'être appellés à l'école polytechnique, d'où ils ne sortent que pour remplir des postes importans que le gouvernement leur confie); que le cours d'histoire naturelle, de physique et de chimie servent d'introduction aux états d'officiers de santé de toutes les classes, et que la chimie conduit à la perfection des procèdés employés dans les manufactures, telles que les blanchisseries, les tanneries, dans l'art des teinturiers et des salpêtriers, etc. que les cours de grammaire générale, de belles-lettres, d'histoire, et de législation forment des hommes de loi, etc. Enfin il est clair que toutes les classes de la société doivent retirer un profit plus ou moins direct de l'ensemble des connoissances présentées à la jeunesse dans cet établissement, placé d'ailleurs sous l'influence de dix professeurs qui consacrent tout leurs temps aux différentes branches qu'ils enseignent….".*

quite enough Latin was already being taught.[45] Well into the 1820s and beyond the ministers of state were searching for the right formula for teaching applications in the lycées and the schools of "arts et métiers."[46]

Thanks to a set of revolutionary ministers, among them the chemist, Chaptal,[47] after 1800 there was barely a place in Western Europe, and even in the newly independent American states, where what we would call applied science, escaped valorization. Even sugar cultivation in Cuba, it was said, should be "guided by scientific principles."[48] In the new scientific culture that matured in the eighteenth century, first in Britain then on the Continent, science bled into technique, and both served the cause of technological innovation. Wrapped in the mantle of practical but formal learning, Western industrialists made a place for themselves in towns and cities over which they gradually became economic and then political and cultural leaders.

Science bled into technique, and both served the cause of technological innovation

Further British examples

Such a knowledge base that we see by the 1780s had not always been in place within entrepreneurial circles. In the 1750s a quite prosperous wool spinner and merchant in Leeds - who left a 40 volume personal diary - evinced not a scintilla of scientific knowledge.[49] Within a generation the knowledge and skill possessed by Leeds factory owners had changed. Because of the difficulty of mechanizing wool weaving we do not think of woolen textile manufactures as being at the cutting edge of industrial development. In 1792 the leading woolen and worsted manufacturing firm consulted with Boulton and Watt about installing a remarkable 40 horsepower steam engine, and Benjamin Gott, its most mechanically proficient partner, became a consultant in the region on engineering problems. He also pioneered the use of steam in the process of wool dyeing (weaving mechanically would take many decades to perfect).[50]

Gott also became an expert on a hydro-mechanical press, or Bramah's hydraulic press as it became known, a large and complex piece of equipment introduced late in the century, requiring

[45] *AD du Nord, MS 2T 1208 Enseignement Secondaire et primaire, Généralités, 1812 - 1852, Rapports d'inspection en executant au decret du 15 novembre 1811: 1812-1813, Académie de Douai, L'Inspection à Monsieur le Recteur de l'Académie, Hazebrouck, 6 juin 1813, No. 1 Collège d'Armentières, "Les classes des Mathématiques composée de 7 élèves est extremement faible surout quand on considère qui M. Piette a été professeur dans une école centrale et dans deux lycées. Il paraît condomné à une longue médiocrité; on ne gagne guère à son âge; les meilleurs élèves de cette classe seront peut être bons à noter une autre année...." Académie de Douai, L'Inspection à Monsieur le Recteur de l'Académie, Hazebrouck, 11 juin 1813, No. 3 Collège de Bailleul, "...on reclame l'enseignement des mathématiques comme indispensables et comme devant faire fleurir le collège; c'est le voeu de toute la ville, on le demande pourquoi le Collège de Bailleul à trois Régents de latinité, lorsque celui d'Armentière qui est d'une tout autre importance, n'a que deux régens de Latinité qui suffisent au Service plus un régent de Mathématiques....".*

[46] *Archives departementales, Seine-Maritime, MS XIX H 4, circulaires et instructions officielles relatives à l'instruction publique, 1802-1900.*

[47] Horn and Jacob, 1998, p. 671-698.

[48] Quoted in Portuondo (2003, p. 246).

[49] This example comes from the rediscovery of material that had been in the public domain but ignored; Jacob and Kadane, 2003, p. 20-49. See also the trade notebook of a clothier, Leeds Record Office, MS GA/B27. A similar transition in educational level can be seen in the post-Civil War American textile industry, "for the postwar world of powered manufacture...sons would need more: an understanding of mechanical principles, capacity to innovate in design, an ability to coordinate production on a grander scale". Quoted from Philip Scranton (1986, p. 46).

[50] Brotherton Library, University of Leeds, Gott MS 193/3/f. 98, letter of Davison to Gott asking him if he would go with him to give his opinion of their steam engine to Mr Goodwin..."but if you can't here are queries in writing". Dated 1802 5 May. On the engine and its many uses for scribbling, carding, turning shafts and gearings, stones to grind dyewood see Heaton (1931-32, p. 52-53).

an understanding of levers, weights and pulleys, air and water pressure and used to imprint patterns on textiles.[51] He carefully compared the relative merits of prototype machines offered by rival manufacturers of the device, but the machine met the fierce opposition of his workers and may never have been systematically used for years.[52] The hydro-mechanical press raised an enormous weight to a small height by using a strong metallic cylinder, accurately bored and made water tight, and it was connected to a small forcing pump.[53] By means of valves, pumps and levers, cisterns and water pressure, 400 pounds of pressure was accumulated and then released.[54] The press was to be used to apply patterns to worsted just as it had been used in applications to cotton. It called upon just about every principle learned in Newtonian mechanics as taught from Desaguliers to Dalton, and no semi-literate tinkerer in the country could have made sense of it. The knowledge economy advanced in the textbooks lay embedded in the cotton and wool factories of the 1790s.[55]

The Gott firm and family also became leaders in the civic and industrial life of Leeds. Just like the Boultons and the Watts, the M'Connels and the Kennedys, the Gotts and their local equivalents, the Luptons, Marshalls, Adams and Walkers, established themselves as leaders of a new Philosophical and Literary Society (first chaired by Gott). They and the other seventeen proprietors subscribed £100 for a building to house the society and put out £350 for scientific apparatus.[56] They invited Dalton to be their first lecturer, and not least they commissioned a bust of James Watt intended for display.

In 1821 the opening lecture at the Society valorized the scientific culture here described, and linked it to striving and the industrial order: "the thirst for improvement gives an exaltation of character... produce[s] the works of genius and the discoveries of science...science, no longer confined to the closets of the learned, is applied to the comforts and amelioration of mankind. Its influence is strikingly apparent alike in our houses and manufactories."[57] The historical sources, on this occasion left by woolen manufacturers in Leeds, present science and its methods as lying at the heart of a set of values, beliefs, and deployed technological systems, in other words, of a new culture at work at the heart of early industrialization. Scientific acumen was not just cultural capital, as was once maintained, it was also deployed and wo-

The knowledge economy advanced in the textbooks lay embedded in the cotton and wool factories of the 1790s

[51] *The Brotherton Library, MS 193/ 3 f. 94.*

[52] *Ibid., f. 97 Gott to Bramah from Leeds 29 March 1809 on his hydro-mechanical press: "We have from your letter of the 25th instant that the sale and general adoption of your patent presses have been prevented by unfavorable representations respecting the merits & utility of the one you erected for us... we must ...tell you that we look after every operation of the work ourselves, and if we had experienced any advantage from the use of your press, we should have insisted on those men working it, or we should have appointed others in their places who would have been obedient....". See Heaton (1931-32, p. 58) who takes a dimmer view of Gott's success in putting the machine to work.*

[53] *Randall, 1991, p. 43. And for the Gott papers see Leeds University, The Brotherton Library, Special Collections, MS 193/132-192 Benjamin Gott & Sons: Business Letters, 1818-1847, MS 193/32-73 Wormald, Fountaine & Gott: Business Letters, 1792-1795, MS 193/85-88 Wormald, Fountaine & Gott; Miscellaneous Records, 1795-1800, MS 193/74-84, Photostat copies of letters, 1792-96, in Boulton & Watt MSS in Birmingham Public Library.*

[54] *For a more detailed description see Tilloch (1825, p. 145-147).*

[55] *Note that tool making, unlike heat engines, water motors, bridge building, etc received little guidance from scientific principles until the 20th century; see Gordon (1988, p. 744-778).*

[56] *Leeds University, The Brotherton Library, Special Collections, MS Dep. 1975/1/6, 7 May 1819.*

[57] *Thackrah, p. 23-24.*

ven subtlety into the fabric of mechanized factory life.[58]

What can be concluded

Partly in response to understanding the relationship between eighteenth century science and technology described here, increasingly, economic historians like Joel Mokyr and historical sociologists like Jack Goldstone argue that technological innovation spurred the industrial revolution and that "the expansion of both kinds of power [water and steam] was driven by exactly the same underlying culture and practice of engineering and development of mechanical power and its application to production."[59] Mokyr talks about how the expansion of useful knowledge became the key to the first Industrial Revolution, and uses the felicitous phrase "industrial enlightenment" to describe the new industrially- relevant culture found in late eighteenth century Britain.[60] Goldstone finds that description too general, and further identifies a very specific form of useful knowledge as necessary, a "greatly improved and expanded knowledge of the physical processes underlying power generation and applications, and the manipulation and creation of physical materials."[61] In other words, Goldstone designates as specifically modern, economic growth "founded on the continual and conscious application of scientific and technological progress to economic activity."[62]

Mokyr talks about how the expansion of useful knowledge became the key to the first Industrial Revolution

Laying emphasis upon science and technology as they were configured in the past cannot, however, lead to a new form of cultural determinism. Culture limits and permits, it does not determine. Only an Hegelian idealist would argue that ideas - or broadly stated culture - set the course of history.[63] In the title of a forthcoming book, Jack Goldstone describes the First Industrial Revolution in the West as "a happy chance." He sees a fortuitous confluence of economic, political and technological factors that for two or more generations gave Britain a distinct advantage and that led to unprecedented economic growth. It is certainly the case that in 1650 no one in England or Scotland would have predicted the political stability, economic conditions and scientific culture that made the First Industrial Revolution happen. By 1750, at the least, all of those factors were present, and in 1766 we find Josiah Wedgwood writing to a friend, "Many of my experiments turn out to my wishes, and convince me more and more, of the extensive capability of our Manufacture for further improvement... Such a revolution, I believe, is at hand, and you must assist in, [and] profit by it."[64]

If historical change is random, a gambler's gaze has got to factor in a good hundred years of trends, and avoid making any facile separation of politics from culture, science from technology, and all from economy. Nothing that happened in the cultural life of eighteenth century Britain can be divorced from the relative stability

[58] *As argued in* Thackray (1974, p. 672-709).
[59] Goldstone, 2005, p. 7. *Here he is taking issue with the work of Nicholas Crafts and C. Knick Harley in particular.*
[60] Mokyr, 2002.
[61] Goldstone, p. 8.
[62] Goldstone, 2002, p. 334.
[63] *For a theoretical approach to culture and sharing my view of its relationship to economic life see* Jones (1995, p. 269-285).
[64] *Letters...*, 1903, p. 165.

and political liberties put in place decisively in 1688-89. I do not think that culture made the First Industrial Revolution, but I do think that a particular scientific culture had permeated more deeply into British education, formal and informal, than was the case anywhere else on the Continent. That culture played a vital role in the complex process by which manufacturing was industrialized. I know nothing about China beyond what I read in the work of others. Those experts, when they make comparisons with the European pattern, do need to nuance their understanding of science and technology, to historicize them.

There is another reason for laying emphasis upon scientific culture. Arguably, without securing their social place the first generation of industrial entrepreneurs would have been outliers, in that the knowledge and techniques they had perfected for innovation, particularly in steam and factory, would have remained confined to their businesses and their heirs, and not have become harbingers of a new social and economic order wherein industrialists had to be accommodated politically, and where entrepreneurs quickly came to be envied and imitated. They competed for social leadership with an urban gentry and landed aristocracy. Their assumed superiority meant that at the Great Exhibition of 1851 their taste - in everything from furniture to spoons - was exclusively on display - in the vast wing that complimented the machines.

The new industrial entrepreneurs survived not as social anomalies, but as exemplars of a new industrial future. They consolidated their position in town after town by putting their scientific culture to work for them. They set up literary and philosophical societies, mechanics' institutes, museums and exhibitions dedicated to science and industry. We know that into the 1850s much manufacturing continued to be hand, and not machine or power, although by then everywhere handcraft was threatened by power technology. Also, by then a recognition existed in many parts of the world: what the British, the Belgians, the Swiss, the Americans, more slowly the French and the Dutch, were doing with machinery had to be imitated. Industrial competitiveness required being at the forefront in both science and technology.

The new industrial entrepreneurs survived not as social anomalies, but as exemplars of a new industrial future

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