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MECHANICAL SCIENCE ON THE FACTORY FLOOR: THE EARLY INDUSTRIAL REVOLUTION IN LEEDS

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We think of mechanization in the late eighteenth century and we think, textiles. And as a result of the work of Musson and Robinson, Ian Inkster, Larry Stewart, myself and others, we now consider the role of mechanics, pneumatics and hydrostatics in a variety of industrially relevant settings: steam applied to cotton factories, or mines and canals, or new methods used in the dredging of harbours or in the raising of water from north country coal mines or London's Thames.[1] We also associate all those applications of power technology with the scientific culture and experimental habits that took root in eighteenth-century Britain. That culture and the habits associated with it, in this instance as demonstrated in the factories of Leeds, form the core of this essay. In Leeds we are about to find scientifically-informed, shop floor experimentation that transformed the woollen and linen industries. Decades ago Musson and Robinson opened up the possibility that such a mindset — with a knowledge base informed by science, wedded to trial and error, constantly manipulating devices to improve production — might have been front and centre in the technologically most advanced epicentres of early industrial development. Now the evidence is mounting for the precocious nature of their insight.

This essay offers new evidence to document the debt early industrialists owed to mechanical science and to chemistry. In their workshops, where new machines and new applications of existing machines became the goal, science and technology were closely intermingled, not hierarchically but dynamically, never one and the same thing, but never far apart.[2] We may even borrow a phrase and describe the entrepreneurs that interest us as "hybrid savant-technologists".[3] By 1800 they and their Yorkshire factories provide a vivid example of a distinctive form of material culture, now known as "techno-science", present in this case far earlier than the twentieth-century invention of the term would suggest. In the critical first generation of mechanization that began in the 1780s, linen and wool manufacturers in Leeds, like their counterparts in Manchester, deployed scientific knowledge of a mechanical sort — and chemistry — to assist in the invention of new industrial processes and forms of industrial life.[4]

Neither the technology nor the science should be reduced one to the other nor assumed to resemble a simple distinction, invoked increasingly in the nineteenth century, between the work of scientists and engineers. By 1790 that division of labour was visible — but in embryo. Sometimes theories and calculations were involved; it became possible to speak about "the theory of wheels". Other times innovative, as well as repetitive, making and doing with machines consumed time and labour.[5]

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Sometimes — in the same person — the thinking relied upon words, theories and numerical symbols, other times it was tactile and visual in nature.[6] Because we have the historical record left by the words — the machines having long since disappeared — emphasis will be laid here upon scientific knowledge. But make no mistake about it, technology, the invention, manipulation or improvement of machines for making cloth or deploying engines for increased power, was ever present, even if harder to recapture. When our Leeds manufacturers thought with scientific words, distinctively, the science employed came from Newtonian mechanics (as well as from the latest chemistry). These knowledge systems received application on the factory floor, and theories and methods, both experimental and mathematical, were applied *inter alia* to bobbins, to the weight, friction and velocity of wheels, to the gravity, elasticity and combustibility of atmospheric air, to dyeing and whitening.[7] Frequently the approach to machinery relied upon a scientific style of thinking that sought general principles and employed experimental techniques. Entrepreneurs relied upon habits of replication, and the search for generalizations about the relationship between weight and force such as could be derived from eighteenth-century scientific textbooks and lectures.

LEEDS

The generation of the 1780s to the 1820s proved economically decisive in cities like Leeds, Manchester, and Birmingham.[8] By the 1790s the front-runners in the industrial race knew that what they were experiencing was unique and commented upon it extensively.[9] Leeds, with its canal to Liverpool, stood at the centre of a north-country district experiencing rapid industrial development. The extant archives demonstrate that those economic developments possessed intellectual underpinnings. New scientific knowledge worked in the minds of leading textile manufacturers who became central to Leeds's economic transformation. And Leeds is not the place or time where we would expect to find industrialists possessed of expanded knowledge about the physical processes fundamental to power technology. At the time neither linen nor wool cloth (unlike cotton) could be woven mechanically. Yet all the technological and scientific practices I am about to describe, facilitating the cutting-edge application of power technology to manufacturing, appear in Leeds at least a generation before either fibre could be made into cloth by power-driven machinery.[10]

Leeds, Birmingham and Manchester, in the same period, can now be shown to possess a remarkably similar scientific culture. We know that Manchester cotton manufacturers used a technical and scientific knowledge-base that facilitated their adaptation of power technology.[11] Now we can demonstrate a similar phenomenon among Leeds manufacturers. As in other industrial settings, manufacturers in Leeds learned the same lessons from textbooks and lectures in natural philosophy — they learned science often cast in an applied direction — then they did something not often attempted by the natural philosophical (or scientific) lecturers or writers, they brought to their own technology new conceptual tools. In the process they adapted mechanical knowledge to the particular needs of their industry. The application of power technology, most dramatically in the form of the steam engine, advanced the factory as the setting favoured by entrepreneurs. It soon became the most accommodating place for manufacturing, to be imitated by all competitors. The material from Leeds affirms the thesis of there having been a specifically *scientific* culture that offered knowledge that became fundamental to power technology.[12]

Mechanical knowledge was not simply grafted onto an existing set of economic conditions. It also helped to shape those conditions — expensive and powerful engines made factories all the more functional and necessary — just as the content and form of the discipline of mechanics became increasingly applied, routinized and expanded upon in factory after factory. Gradually but steadily, cloth merchants became manufacturers who centralized production — despite opposition from hand workers and smaller scale merchant weavers.[13]

CURRENT HISTORICAL AND SOCIOLOGICAL READINGS OF THE EARLY INDUSTRIAL REVOLUTION

Partly in response to the work of the historians of science and technology cited above, 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".[14] 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.[15] 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".[16] 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".[17] Both Mokyr and Goldstone award agency to culture, as do I. The older historiography rested explanatory power upon assumptions about the centrality of material causes — coal, capital, surplus population — and about manual skill — not the knowledge base — "of semi-literate tinkerers", to use the oft-repeated phrase. The aesthetic underpinning this essay, despite its emphasis upon the knowledge base, would in the end find explanations in multiple agencies, mental, tactile, cultural and material. If we are to present an historical voice that articulates the complexity of the first industrial sites — unprecedented in the world — then the many skills at work on the factory floor need to be accounted for. We need to move beyond false dichotomies, science *v.* technology, culture *v*. coal and capital.

Historians of science like Ursula Klein argue for the relevance to industrialization of a particular configuration of science and technology. She posits an expanded historicity for techno-science which, using the case of German chemistry, she takes back well into the eighteenth century, even before its industrial application.[18] Predictably she, and many of the historians of science cited earlier, see science as shaped by the material culture, or physical setting, in which it lies imbedded. And by the late eighteenth century these were many and varied. To the classrooms of the dissenting academies and universities, the lecturing rooms of the itinerant teachers of science, the chemical workshop, and the rooms of the scientific societies must now be added a new setting: the industrial factory of late eighteenth-century Britain.

Other older assumptions about what industrialization requires are also now being discarded. Both Mokyr and Goldstone are unimpressed by the argument that the mechanization of cloth required not steam, but only jennies and water power. A version of that argument applied to Leeds would have it that power technology and the knowledge base used to assist in its deployment had little to do with the wool industry until it could be applied to weaving. I too find the historiography from the 1970s unconvincing for its failure to take into account the fact that steam engines were involved in so many aspects of textile production, from spinning and rolling to dyeing. Of course, water power remained undeniably important, particularly where a ready supply was available. But the water wheel could not provide the versatility of the steam engine.[19] Contemporaries labelled steam as the "most useful and most formidable power; where the work is of that magnitude and importance to afford the expence of erecting and working a steam engine". If the quantity and downward force of water was not present, steam became "best and most effectual", yet enormously expensive tool requiring not only fuel but a mechanic who "perfectly understands the construction of all its different parts".[20] Cutting edge entrepreneurs possessed the necessary capital for such an investment, to be sure, but they also deployed a cultural capital that valorized experimental habits. These were employed to improve upon machines, most formidable among them, steam engines. Their use expanded exponentially decade by nineteenth-century decade.

In one respect the older historiography did credit science with playing a role in early industrial life, if only because scientific culture gave social identity to men who largely before 1830 were outliers from the social and political élite.[21] Where they showed an interest in science, that historiography argued, it fuelled social prestige. But the argument does not go far enough. Now we can add that science also informed practices on the shop floor. In this period what was designated as scientific or natural philosophical imparted both mechanical knowledge and experimental methods, with chemistry just beginning to be important. As we shall see, once learned by entrepreneurs, whether in wool, linen or cotton, both scientific method and knowledge, whether mechanical or chemical, made their way on to the shop floor. More was at stake than simply the status earned by establishing literary and philosophical societies or mechanics' institutes, as important as they must have been for valorizing social prestige and diffusing useful knowledge.[22] The learning of mechanical science and its experimental protocols could and did transform shop floor practices.[23]

The contemporary approach being taken to the role of science in the early Industrial Revolution, as evinced by Mokyr, Goldstone, Klein, Stewart, myself and others, stands in other respects in contrast to what had been commonplace in the literature about early industrial development well into the 1980s. Then it was fashionable to say that industrialization *tout court* had nothing to do with science, that it critically depended upon the work of "semi-literate tinkerers".[24] It seems fair to say that present-day commentators who elevate technical and scientific knowledge, and focus on the interface between science and technology, do not mean to deny that skilled 'tinkerers' were found in abundance in the cloth industry, before the advent of the factory, and well after it. They brought their skills to bear in a variety of vital tasks. In the production of wool cloth they could card and scribble, spin, full, weave and dye. They had considerable technical knowledge of the elaborate processes by which wool became useable cloth or worsted, or flax became linen. They could build and fix machines such as jennies. In the 1760s machine makers spoke knowledgeably about "engines", for example, meaning a device that "worked bye a screw that is ... the first movement of your friseing mill and the weight lyes on the upright shaft and a new thing that rides on a pin will turn great weight with much ease".[25] In short, as well as visual and tactile knowledge, oftentimes artisans and machine makers possessed mechanical knowledge about screws, levers, weights and pulleys, such as could be found during the eighteenth century in the many editions of Joseph Moxon's *Mechanick exercises* (1683, 1693, 1703, etc.) or William Emerson's *Principles of mechanicks* (1754, 2nd edition 1758).[26] These technical men deployed a knowledge base that, in the terms of a slightly earlier age, laid emphasis upon *praxis* or *experientia*, but not upon *episteme* or *scientia*. But principles of central forces, theories of motion, and squares of velocities came directly out of the science of the day and mastering that knowledge meant addressing the basic skills now available.

A QUANTITATIVE AND QUALITATIVE CHANGE IN SCIENTIFIC KNOWLEDGE

Contemporary historians and sociologists see more mechanical knowledge more widely available in Britain by the 1780s than elsewhere, and as being actively and publicly deployed.[27] We also recognize that the Newtonian synthesis qualitatively altered both celestial dynamics and terrestrial mechanics, that it unified mechanics as never before. Its principles were then explicated in textbooks that began to appear in Newton's lifetime (d. 1727) and that were remarkably similar in approach if not content from Desaguliers through to Dalton.[28] With increasingly successful application came the realization that deployment increased profits. In Leeds, as in Manchester, the key innovators, the pace-setters in the spinning factories of the 1790s and beyond, measured the value of what they knew in speed, as well as time and labour saved.[29] Knowledge of how and why spinning machines and steam engines actually worked — of friction during rotation, of the relationship between weight and speed, of the effects of air pressure, of the centrifugal principles employed by the engine's governor — was necessary before the economically risky step of deploying them could be undertaken with maximum success.[30] If for no other reason such knowledge insulated against fraud, and as Larry Stewart has shown, there were plenty of bogus schemes being peddled by the gullible or the shrewd. Addressing entrepreneurs, natural philosophical lecturers from Desaguliers onward eagerly told them what they needed to know: "The steam engine ... cannot be understood without the previous explanation of Mechanics, Hydrostatics, and Pneumatics."[31] James Watt would have added the necessity of reasonably sophisticated mathematical skills such as he had acquired through his study of the Newtonian explicator of the 1720s, W. J. 'sGravesande.[32]

Eventually, by the 1830s, the knowledge once promoted by natural philosophical lecturers and Newtonian textbooks would become the possession of the ubiquitous engineers who, for example in Leeds alone, by 1824 had installed 129 steam engines that, according to a contemporary witness, generated at least 2318 units of horse power (hp).[33] Steam power could assist in spinning (but not weaving) threads and its boiler used for a stage in the dyeing process. Wool could also be dressed by steam driven machines.[34] By the 1830s the weavers and fullers who aspired to become overseers of engines, or mill owners themselves, came to see that the manufacturing world of the West Riding had been transformed irreparably by a mechanical knowledge that they too needed to possess. And the new mechanics' institutes sponsored by manufacturers in nearly every town offered it to them. By that decade the publican James Kitson gives valuable evidence of what could be learned at such an institute. He described what he did not know — before he attended the Mechanics Institute in Leeds — in the following terms:

> I had obtained an ordinary day school education, as a knowledge of the simple rules of arithmetic, but was completely ignorant of the most simple parts of philosophy. I knew that steam caused the steam engine to work, but I did not know how or why; I knew that the pump caused water to rise out of a well, but I also believed that it was through the agency of suction, and I thought its power was unlimited as to extent.[35]

Through education Kitson acquired a detailed knowledge of steam and mechanics in general, and went on to become a prosperous engineer and a political reformer in the Whig tradition. The libraries and technical apparatus owned by the institutes attest to the importance awarded to learning mechanics and to observing, as well as handling, steam engines, air pumps, and by the 1830s, electrical devices.[36]

Focusing on the ceaseless striving of industrialists, their contemporary critics and imitators like Kitson observed the historical experience I seek here to recapture. A generation earlier in Leeds opponents of the new machinery described technology as critical, that the effort "to convert our wool into cloth ... by mechanical contrivances, without the intervention of human labour" had become "a race amongst individuals". The private greed of industrialists puts "the public good ... out of the question. It is in reality, each one striving against the rest, by every possible means, to draw to himself a large proportion of the business ... mechanical contrivances [are employed to accomplish this]; every one endeavouring to carry them farther than another for his own particular advantage".[37] By 1800, and well before, critics and entrepreneurs alike knew that more efficient machines were vital to economic success, that speed and efficiency equalled time and labour saved, profit earned. Perhaps their enemies did not know about the time the soon-to-be-wealthy savant-technologists also spent studying and applying the science of their day.

THE MARSHALLS (AND THE GOTTS)

In the 1790s the engines deployed most notably by the Leeds manufacturers, John Marshall in flax and Benjamin Gott in wool, operated machinery involved in nearly every other aspect of the process by which both fibres were readied for weaving, and dyed or processed, once woven. As a consequence Marshall and Gott became the wealthiest and most influential cloth makers in the town.[38] What they knew about mechanization, and applied in their factories, laid down a template for others to emulate or envy. Gradually they became civic and political leaders. By the 1830s power shifted away from the landed gentry and toward men like Marshall who took their seats in Parliament. At his death in 1840 he was worth well over £2,000,000. He had built multiple flax spinning mills, acquired a country estate, and fortunately for us, saved various notebooks that document his participation in the scientific culture of the late eighteenth and early nineteenth centuries and its application in the mechanization of his factories.

No one carried the mechanical contrivances for their own advantage — to paraphrase their critics — further than John Marshall and Benjamin Gott. In the 1790s both installed 40hp Boulton & Watt engines in their factories, and by 1824 Marshall's various flax mills used five or more engines, with the largest producing 71hp and made by his associates, Fenton & Co. But did he understand how these engines worked? From detailed notes taken by him at the time, we know that in 1790, at a large room in Hodgson's Academy, Marshall attended a set of 15 lectures given by the itinerant lecturer, Mr Booth (see Figure 1).[39] These dwelt extensively on mechanics, hydrostatics, pneumatics, chemistry, astronomy, optics, electricity, pumps, and as we know from Marshall's lecture notes, one was devoted entirely to the steam engine and other devices.[40]

Given the content of the chemical lectures, we can with reasonable confidence identify Mr Booth as loosely a follower of Priestley's phlogiston theory. Eric Robinson tells us that a "Mr Booth" is mentioned in a letter of 1783 to Joseph Priestley where it

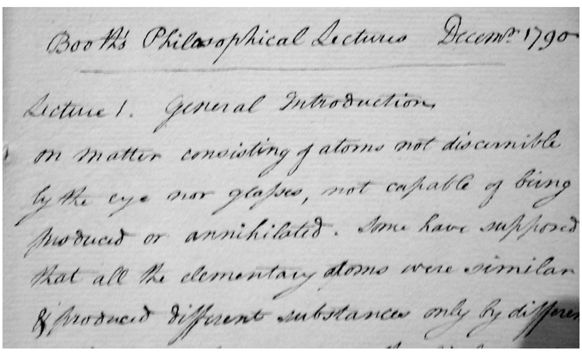
Booth's Philosophical Lectures Decemr 1790
Lecture 1. General Introduction
On Matter consisting of atoms not discernible
by the eye nor glasses, not capable of being
produced or annihilated. Some have supposed
that all the elementary atoms were similar
& produced different substances only by differen

FIG. 1. Marshall MSS, MS 200/42, John Marshall's notes on Mr. Booth's Philosophical Lectures, December 1790, the opening lecture. With kind permission from Special Collections, The Brotherton Library, Leeds University.

is said that he is seeking a recommendation. While one cannot be absolutely certain, this is most probably Benjamin Booth, a natural philosophical lecturer of the period who was involved in the circles of the 1790s associated with support for the French Revolution.[41] The association of radicals and scientific circles was a commonplace of the time. Of course, from 1767 to 1773 Priestley was the minister at Mill Hill Chapel in Leeds, a Unitarian establishment that the young Marshall (b. 1762) attended.[42] We can only wonder if Priestley, by 1790 relocated to Birmingham, might have urged Booth to tackle Leeds, or recommended him to members of his old congregation. Perhaps someone from the Gott family was also present at his lectures as the family can be associated with such interests. One John Gott (d. 1793) — possibly related — appears on a membership list of a dining club of engineers who from 1771 met around John Smeaton. Benjamin's half-brother, William, left behind a notebook filled with engineering terms and their definitions.[43] The Gotts, like the Watts, had scientific knowledge in the family.[44]

When advertising his upcoming lectures in the *Leeds intelligencer* for December 1790 Mr Booth claimed that he had invested over £4000 in his demonstration equipment and that, in aggregate, it weighed over 7 tons.[45] Even allowing for exaggeration, this was a formidable arsenal that must have included air pumps and orreries, levers, pulleys, hydrometers, electrical devices, and, here I am going to hypothesize, possibly a small steam engine, or its replica. Perhaps only something quite that big would have given Mr Booth substantial tonnage, even if it was not as much as he was claiming. We know that such demonstration replicas existed because early in the next century instrument makers listed them in their catalogues, and two decades before Booth lectured, John Smeaton informed James Watt that he had gone home and built one so as to test out Watt's claims about the energy that his engine could deliver.[46] The Victoria and Albert Museum possesses a single condenser engine from the late eighteenth century that was built on the scale of 1 to 12.[47] Detailed printed lectures on mechanics in this period also employed engravings that depicted all the parts of the engine.[48] In 1799 Adam Walker's natural philosophical lectures included a list of the machinery found in his Winter Lecture Room, in Conduit Street, Hanover Square, and it included "Boulton, Blakey, Smeaton's and the common fire or steam engine". He claimed that they could not be removed because of their size, and were used to illustrate the lecture on mechanics.[49] The possibility that Booth also displayed demonstration steam engines takes on addition plausibility when he tells the forty subscribers he seeks to enroll (at the cost of one guinea each) that he can give only one course of lectures in Leeds because he has obligations in Birmingham.[50] Although not — as far as we know — a member of the Lunar Society, Booth would seem to belong on its fringes.

Itinerant lecturers were well known in manufacturing circles. Josiah Wedgwood, whose own factory worked also as an experimental site, was in constant communication with chemical and mechanical lecturers such as William Lewis and James Ferguson.[51] The Scottish lecturer in mechanics, Dr James Dinwiddie (b. 1746) who travelled Britain giving lectures in "Mechanics", displayed interest in topics directly relevant to manufacturing: the speed of water wheels, the most efficient and accurate pendulum clocks, the best use of pulleys, friction in mill works, the best methods of pumping water, the dimensions of carding machines, rotative motion, the best metal to use in lathes, and not least and of more general interest, "why should a diminution of gravity produce a slower motion at the equator".[52] This university-educated student of natural philosophy took extensive notes on every machine that he saw and left an experiment book that shows him examining how better to dry silk and remove cataracts while also using electrometers and microscopes. He did chemical experiments, attempted to etch glass, and tried to figure out "the degrees of heat at which water boils under different pressures of the Atmosphere". He also followed Watt's experiments on the temperatures generated by steam.[53] His mind was both theoretically and practically trained, and all natural phenomena as well as human artifice interested him. Lecturers knew that to make a living they had to offer improvements in a wide variety of enterprises. Even Richard Watson, a chemical lecturer in such an apparently abstract place as Cambridge, argued that "the uses of chemistry ... in every economical art are too extensive to be enumerated".[54] In town after town, when these lecturers travelled they were basically chasing after the same audiences as was Mr Booth.

The Leeds audience of Mr Booth probably had quite a few manufacturers with "economical" interests, although only Marshall — as far as we now know — left such a detailed account of what Booth said. By dwelling on his lectures, as revealed and filtered through the notations made by Marshall, we get closer to the scientific way of thinking that cloth entrepreneurs could imbibe at such lectures, as well as from reading in scientific literature, also annotated in the same note book where Marshall recorded what he heard at Booth's lectures. Before turning to Marshall's detailed discussions of the many "experiments" — to use his word — that he undertook on his factory equipment and in dyeing, experiments that began in the late 1780s and continued into the next generation of Marshalls who inherited the mills,[55] we want to know what Marshall learned in those wintry afternoons or early evenings at Hodgson's Academy.

In a format typical of eighteenth-century scientific courses in the Newtonian tradition — from Hawksbee to Dalton — Booth began with the very structure and uniformity of matter.[56] Throughout I quote from Marshall's notes on the first and subsequent lectures: "On matter consisting of atoms not discernible by the eye nor glasses, not capable of being produced or annihilated ... 5 properties of matter considered, its extension, solidity, divisibility, capability of motion & vis inertiae."[57] Although not noted by Marshall, almost certainly at this point Booth would have gone on to explicate universal gravitation and the laws of local motion. Certainly we know that "The different attractions of matter were considered the attraction of cohesion, of gravity, of electricity ... & a long dissertation with several experiments on elective attractions, the knowledge of which is of great importance to chemistry & mineralogy".[58]

In the same first lecture Booth mentioned phlogiston and described an experiment "made of burning a piece of iron wire in a bottle of pure air which being lighted at one end burnt entirely away melted & dropped down reduced to a perfect calx". Immediately its industrial application follows, "which shows the wonderful effect that would be produced by blowing pure air into furnaces instead of common air for no furnace will melt wrought iron ...".[59] In the lecture on pneumatics the weight of atmospheric air on a man [and hence on a machine] is given as the equivalent of 37 tons.[60] The first lecture set the pattern of all the others. Theory mixed effortlessly with the most basic applications, science with technology, with explanations of how syphons and pumps worked, including one said to have been invented by Booth. The discussion of the best method for raising water is followed immediately by Newton on the tides, "Newton attributed the tide on the opposite side of the earth from the moon to the solid part of the earth being more attracted than the water on the opposite side & being as it were drawn away from it" (see Figure 2).[61]

The detailed lecture in hydraulicks discussed the commonplace errors in the construction of pumps, that is "placing the low valve too high ... it ought to be placed as near as possible to the surface of the water because there the water ascending acts with the greatest velocity and force", as well as making the windbore of a lesser diameter than the working bar when "they ought to be the same diameter". Booth then gave a demonstration of his model pump that moved water by a continuous circular motion.[62] Another pump, he told his audience, could "at a stroke drain water both by the piston's ascending and descending ... the piece of wood then falls to the bottom and raises a quantity of water equal to its own weight at the other end of a beam". On the very next page Marshall recounted Newton on the tides, then noted that another scientific lecturer of the period, James Ferguson, ascribed their motion to "the centrifugal force arising from the earth's moving round its common center of gravity with the moon. The center of gravity is about 2000 miles from the surface of the earth". In the next breath, it would seem — or certainly in Marshall's next sentence — we are told that with pumps vibration decreases velocity, and the best valve or clack to use is a mitred one.[63] The same forces that acted on the pump acted on the tides.

After detailed lectures on astronomy, opticks, pneumatick chemistry and electricity, mechanics followed. As did so many of the natural philosophical lectures of the eighteenth century, this lecture began with basics: the lever.

> There is only one power in mechanics viz the lever — all others are resolvable into this. The quantity of power gained is exactly equal to the time lost. The length of a crooked lever is to be measured by dropping a perpendicular from the fulcrum to the line of direction of the two powers — Friction is equal to the weight & velocity of the moving body, & does not at all depend upon its greater or smaller surface. This was proved by a piece of wood on an inclined plane which required the same weight to draw it up on its edge as on the flat side which had 5 times the surface. The pivots of wheels should be small because of having less velocity but long that they may not wear the steps by having too great a weight on a small surface.[64]

The very next lecture, devoted entirely to water wheels and steam engines, is listed in Marshall's notes, but the details are not elaborated upon. Notes taken on a book about heat, some fifteen years later, detail Marshall's continuing interest in steam and its manipulation.[65]

The time has come to pass from Marshall's rich notes on Booth's scientific lectures — rare though the survival of such notes may be — and turn to the pervasive scientific mind set that Marshall brought to his early industrial and technological activities on the factory floor. I am not arguing that Marshall's approach to mechanical problems derived directly or entirely from Booth. Such an argument would impoverish the multiple sources available to the John Marshalls of the 1790s: conversations with engineers (many of which he recorded),[66] consultations with fellow entrepreneurs, even competitors, the long hours spent tinkering and testing rollers, spindles, dyeing techniques — all were important. But I am arguing that scientific knowledge and methods — in both mechanics and chemistry — remarkably similar to what Mr Booth, and numerous other natural philosophical lecturers displayed — informed the approach Marshall and his engineer employee, Matthew Murray, took on the factory floor. There mechanical science and chemistry became part of the process of application and innovation, whether with regard to machines or bleaching and dyeing techniques.

This was science on the shop floor, and without seeing its role we cannot see the distinct cultural elements that went into the early Industrial Revolution. Nowhere

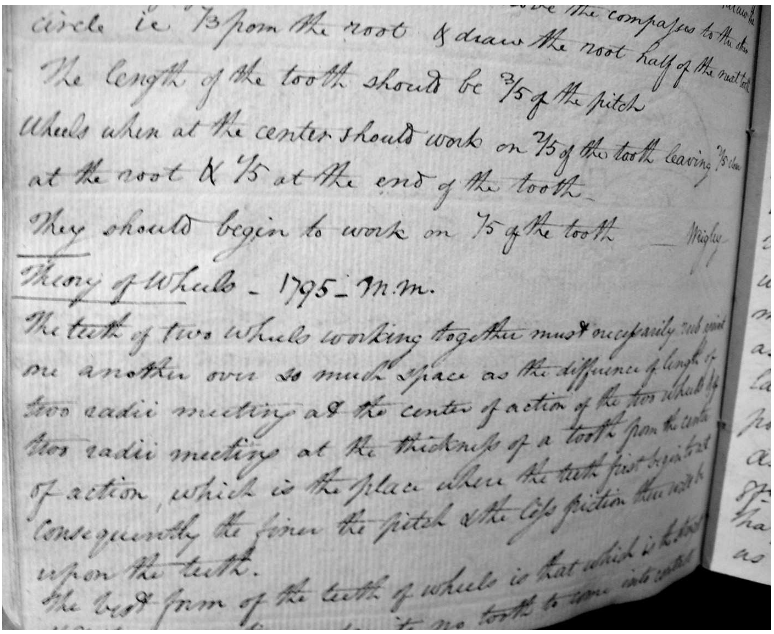
circle i.e. 1/3 from the root & draw the root half of the
The length of the tooth should be 3/5 of the pitch
Wheels when at the center should work on 2/5 of the tooth leaving 1/5 clear
at the root & 1/5 at the end of the tooth
They should begin to work on 1/5 of the tooth
Theory of Wheels - 1795 - M.M.
The teeth of two wheels working together must necessarily rub on
one another over so much space as the difference of length of
two radii meeting at the center of action of the two wheels &
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

FIG. 2. Marshall MSS, MS 200/57, ff. 24–25, "Theory of Wheels", where we see an early reference to Marshall's assistant, Michael Murray. With kind permission from Special Collections, The Brotherton Library, Leeds University.

else in Europe, or the world, did this particularly applied version of mechanical science take hold so early and so decisively, and it contributed to making Leeds by the 1830s the foremost centre for woollen cloth in the Western world. By the 1820s the city and the Marshall firm led the country in linen production.[67]

NEWTONIAN BOBBINS

When Marshall experimented with his equipment in order to improve its efficiency he did so with mathematical precision and with reference to general laws.[68] He was also a consummate technologist, intensely interested in machines employed by others or in other industries, such as those used in cotton spinning.[69] 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 tooth to come into contact but that which is in action.[70]

The form of the tooth is therefore determined by the relative diameters of the wheels which are to work together. Marshall believed that friction occurred most at the exact point where the circumference of the tooth met the wheel. He continues: "To find the true form of the teeth of two wheels of equal diameters draw the pitch line at half the depth of the teeth, & setting one leg of your compasses on the pitch line in the middle of one tooth draw the point of the next tooth with the other leg." Understanding that friction was not a result of velocity, but rather of contact points, created the possibility of its more efficient reduction. Similarly the action of the bobbins as they spun the linen was approached mechanically, by a way of thinking scientifically informed: "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." In addition,

> In the first case the yarn between the flyer leg & the bobbin would have to bear a stress $2\frac{1}{4}$ times as great as at a speed of 2000 revs & the spindle would require $2\frac{1}{4}$ times as much power to give it motion, because the central force is increased as the square of the velocities, & the weight of the bobbin is increased to counteract the increased central force of the thread.[71]

In the latter case of reducing the diameter of the bobbin the stress upon the yarn would be the same as before at a velocity of 2000 revs. Because the central force & weight of the bobbin would continue the same, "the power required for giving motion to the spindle would continue the same".[72] This Newtonian discussion of bobbins continued, "The central force being likewise in proportion to the quantity of matter, a bobbin of the size above described which would not spin 16 lea yarn at a greater velocity than 2000 revs. Would spin 36 lea yarn at a velocity of 3000 revs. a min. In that case the 36 lea ought to be of equal strength with the 16 lea, otherwise it would break the oftener".[73]

How the techno-science worked that called for this application of Newtonian mechanics to bobbins included oftentimes the presence on the shop floor of inventors with multiple skills. In the manuscript folio about "Theory of Wheels — 1795" where the bobbin is explicated appears the initials "M M". In precisely this period Marshall was dependent upon the many innovations that his employee, the engineer Michael Murray, effected in the weaving of linen thread. Dissatisfied with the machines then operating throughout the north, Marshall in his experiment book dated 1788 tells us that "we gave over spinning and set Matt Murray to work on a new loom".[74] For the next five years they sought to find machines that would spin thread as fine, if not finer, than what could be done by hand. They investigated worsted and cotton factories to see what, if anything, could be borrowed from their techniques. The notes left by Marshall contain discussions of tow, slivers, rollers, and carding machines, and after three years of experiments, tell of success: "This plan answered every end we wished, the slivers was level and without patches, the fibers were taken off straight, and we thought it was carded as well as possible."[75] Murray also claimed in 1799 that he had made improvements on Marshall's steam engines that saved fuel and lessened the cost of erecting the engines.[76]

THE CULTURAL VOCABULARY OF EARLY INDUSTRIALISTS

In comparing Marshall's manuscript notebook on Booth's natural philosophical lectures and the experiment book with the initials "M M" next to the discussion of the central force and weight of bobbins, we begin to see a pattern. Engineers like Murray and entrepreneurs like Marshall shared a vocabulary that was scientifically informed just as it was technological. Theory and practice were inextricably entwined; the initials suggest that Michael Murray at the least understood, or at the most, explained this bobbin principle to Marshall. Arguably Murray was to Marshall as Watt was to Boulton, entrepreneurial engineer to mechanically literate entrepreneur. Theirs was a shared vocabulary and its dictionary was both technical and scientific, and of course economic.

The engineer and entrepreneur spoke a language that could lead to enormous financial success, especially, as was the case with Marshall and Murray, when only one of them, namely Marshall, controlled the capital and the profit. Yet in technical matters theirs was a partnership with Murray apparently more the engineer than entepeneur, but also highly literate. For example, friction held one key to economic success, and when not worrying about carding and bobbins, the friction of wheels also occupied the attention of the firm. They wanted to find the best depth of the teeth that would impact the wheel with least friction and yet be deep and thick enough to offer durability. The approach was both experimental and geometrical.[77] Science taught them to generalize, to see the interconnectedness of centrifugal forces at work on the tides and on bobbins. The ability to conceptualize force, velocity and weight was combined with painstaking adjustments and innovations, with trials and errors made on shop floor equipment. The ideas were no good without an unrelenting search to develop new, or improve existing, equipment.

In the experiment books on dyeing and bleaching, the same, interactive pattern between the science and technology of the day holds. Consistently reference is made to the latest experimental work. Marshall took notes out of books by Lavoisier, Berthollet, Chaptal, and Ainsworth, among others. In passing Marshall applied atomic theory, noting that, when oxygenated, muriatric acid "has spent its power, it is common muriatric acid, the coloring particles having taken away its oxygen".[78] Marshall's notes on the *Encyclopédie méthodique* suggest that he read French chemistry without the aid of a translator and that he knew the latest works nearly as soon as they appeared. And always a steady stream of chemical experiments were diligently recorded.[79] There was no contradiction in the minds of Marshall and Murray about how experimental chemistry could inform industrial practice. It made perfectly good sense for Marshall to read among the cutting edge chemists, or to adapt the boiler of his steam engine to steam cloth that he was attempting to dye.[80] It is we who have imposed contradictions, tinkerers *v*. real scientists, trial and error *v*. serious experimentation, science *v*. technology. Or we have wanted to merge the one into the other, refusing to see the variety of skills at play. In the process we have missed the actual merger of the lofty and the mundane, the theoretical and the practical, that distinctively lay at the heart of early industrial processes, particularly those involving power technology.

Once the engines had been installed and the machines made ever more efficient, less rigorous men could copy and improve. The notes taken in the experiment books of the next generation of Marshalls display the same dedication to trial and error but none of the theoretical sophistication seen in the jottings of Marshall with their bows to Murray's expertise. The sons noted how "rolling we have tried as an experiment and found its effect very similar to that of stamping ... there is more expense and more waste in freeing the flax from its matter and caked character before it can be heckled. It is fair to presume that if well managed, there would also be more advantage ... a third method may possibly be found in the agency of steam ... steam may carry away part of the glutinous matter from the fibre...".[81] There is not the same record of restless examination, of interrogations of engineers about which engine, if any, will do the work, nor do we find references to abstract principles. They were no longer needed; the basics of the factory were established and needed now to be improved upon. Perhaps for the second generation science had become so naturalized in family and civic life that its presence of the shop floor could be assumed, or talented employees could be hired who possessed the requisite education in it.

The establishment of a cost-efficient factory took years of trial and error. Early in the 1790s the Gott firm consulted with a variety of engineers on the best engine to install in their factory.[82] Already the leading woollen and worsted manufacturing firm, it accepted Boulton & Watt's offer to install a remarkable 40hp steam engine.

Somewhere in this process Benjamin Gott acquired enough technical and mechanical knowledge that, as the most mechanically proficient partner in the firm, he became a consultant in the region on engineering problems.[83] In an experimental notebook similar to those left behind by Marshall, Gott detailed how his factory manipulated steam engines with varying amounts of water, at varying temperatures, and discovered that "a pound of water therefore in the state of steam contains more caloric than a pound of boiling water in the proportion of 950 to 212. Q.E.D.".[84] Gott also pioneered the use of steam in the process of wool dyeing.[85] As he told an inventor of a hydro-mechanical press with which Gott was less than pleased, "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".[86] Indeed Gott became an expert on a hydro-mechanical press, a large and complex piece of equipment introduced late in the century, requiring an understanding of levers, weights and pulleys and used to imprint patterns on textiles.[87] He experimented to establish the relative merits of prototype machines offered by rival manufacturers of the device, and may have concluded that the device did not work as it should.[88]

THE POWER AND PRESTIGE THAT COULD BE ACHIEVED

The Gott firm and family, along with the Marshalls, also became leaders in the civic and industrial life of Leeds. Indeed Gott's expertise was also sought out by imitators and rivals alike.[89] Just like the Boultons and the Watts of Birmingham, the M'Connels and the Kennedys of Manchester, the Gotts and the Marshalls established themselves as leaders (or proprietary members as they were called) 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.[90] In 1821 the opening lecture valorized public science, 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."[91]

The historical sources, on this occasion left by linen and woollen manufacturers in Leeds, present science and its methods as lying at the heart of a set of values, beliefs, and knowledge systems, in other words, of a new culture at work at the heart of early industrialization. The argument ultimately comes down to the realization that scientific acumen was not *just* cultural capital, it was also deployed and given industrial application. It brought power as well as prestige. Leadership in the industrial cities passed to firms like Marshalls and Gotts in part because their knowledge facilitated the invention and manipulation of mechanical contrivances that replaced human labour. So armed, they could compete aggressively and imagine themselves as superior to the idle and landed of the countryside who still accessed political power.

None of these manufacturers should be imagined as provincials, or ever self-described as social inferiors. Their self-confidence was fuelled by their success, and in the case of the Marshall family social life included the company of Dorothy and William Wordsworth. Mrs Marshall and Dorothy had a friendship from their school girl days and the two families visited and shared confidences in the Lake District. Never do we sense in their correspondence any deference or awe on the Marshall side. The Marshalls knew that their values and learning represented the future.

When Marshall ventured forth into the country — and he adored rural vistas and shimmering lakes — he lamented the backwardness of clergy and landlords alike. In one Yorkshire dale he said that, unlike his own firm that offered evening education to the children it employed, the local clergy were "too idle to put in a school when one is needed". In Swaledale he noted how the "Lords of the Manor" had failed to exploit their lead mines, "what a vast saving would the present state of knowledge in Mechanicks have made them. A steam engine that cost 600 pounds would have been put up in a few months.... It is surprising that steam engines have not yet been applied to lead mines". In Whitehaven he complained how the great part of the town "pays a chief rent to Lord Lonsdale — he has some good houses here uninhabited & going to ruin".[92] In the world that John Marshall and Benjamin Gott wanted, nothing and no one were meant to be idle and that included the minds of engineers and entrepreneurs. Together they and countless other early industrialists brought the new science into places never imagined by its seventeenth-century progenitors. They knew that in combination with technology, science could make new worlds. One of them first emerged on the shop floors of their Leeds factories.

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Revue d'histoire moderne et contemporaine, l (2003), 133–55. The argument presented here builds upon Margaret C. Jacob, *The cultural meaning of the Scientific Revolution* (New York, 1988) and *Scientific culture and the making of the Industrial West* (New York, 1997). Endorsing and expanding on these arguments is Joel Mokyr, *The gifts of Athena: Historical origins of the knowledge economy* (Princeton, 2002), 66. In a forthcoming book, *A peculiar path: The rise of the West in global context, 1500–1850* (Cambridge, MA, to appear), Jack Goldstone will make a similar argument. And see Jeff Horn, "Machine-breaking in England and France during the Age of Revolution", *Labour / Le travail*, lv (2005), 143–66, and *The path not taken: French industrialization in the Age of Revolution, 1750–1830* (Cambridge, MA, 2006).

2. Rachel Laudan, "Natural alliance or forced marriage? Changing relations between the histories of science and technology", *Technology and culture*, xxxvi/2 (Supplement, 1995), S19–22, and I would endorse her conclusion that "it is now generally accepted that there is something distinctive about technological knowledge and that it is neither ... tacit nor simply applied science".
3. Found in Ursula Klein, "Technoscience avant la lettre", *Perspectives on science*, xiii (2005), 226–66, p. 228. For Newtonian science and ballistics, see Brett D. Steele, "Military 'progress' and Newtonian science in the Age of Enlightenment", in Brett D. Steele and Tamara Dorland (eds), *The heirs of Archimedes: Science and the art of war through the age of Enlightenment* (Cambridge, MA, 2005), 361–90.
4. In the period from 1780 to 1800 new professions appeared for the first time in the town: cotton and fustian manufacturers, flax and worsted spinners, printers on cloth, machine makers, pattern makers and potters; see W. G. Rimmer, "The industrial profile of Leeds, 1740–1840", *Publications of the Thoresby Society*, *Miscellany*, xiv/2 (1967), 130–57, p. 135. On the phenomenon of innovation seen more broadly see Helga Nowotny (ed.), *Cultures of technology and the quest for innovation* (New York, 2006).
5. Wolfgang Lefèvre, "Science as labor", *Perspectives on science*, xiii (2005), 194–225, has some useful things to say about the relationship but his vision generally concerns nineteenth- and twentieth-century forms of techno-science. Writing in the same issue, pp. 156–7, Barry Barnes offers a useful discussion of the various meanings given to the term, in "Elusive memories of technoscience".
6. Here I have been informed by the arguments found in Davis Baird, *Thing knowledge: A philosophy of scientific instruments* (Los Angeles, 2004).
7. The Brotherton Library, University of Leeds, Special Collections, Marshall MSS, MS200/42, unfoliated; one page contains this note, made it would seem as the result of reading: "Leslie on Heat 8vo. 1804 communicate to air 1/750 part of the whole heat which it contains, & it will expand 1/250 part of its bulk"; see also MS200/57, Notebook *c*. 1790, f. 1, Steam Engine, gives a list of engines at work in the region with all of their specifics and continues on f. 27 ... undated, including some engines in Manchester; f. 2, "Wrigley says there is nothing gained by a crank instead of a water wheel because of the great weight they are obliged to use at the beam end" (this note undated, but the one below it using a different pen is 1812); f. 17 labelled Speed, "the greatest speed at which they can spin cotton is 15ft a min. or 12 feet a min the day through including stoppages"; f. 23 entitled Boiler, "Wrigley says it should be 4 times diameter of cylinder", dated 1804; ff. 24–25 dated 1795 with these initials given "M.M.", "The teeth of two wheels working together..."; ff. 34–35, Bobbin, "the relative length & diameter of a bobbin must be so proportioned..."; f. 38, Wheels continued from f. 24, "Perhaps the best general rule for the depth of teeth is to make the depth of the acting part 3/4 of the pitch"; f. 38 on strength of wheels, "Rule The square of the thickness of the tooth multiplied by its breadth will give the number of horse power that the wheel is adequate to work, if it move at a velocity of its surface of $2\frac{1}{2}$ [?] feet p. second of time. If the velocity is greater or less, the power is proportionate — The best breadth of a tooth is six times its thickness". See Marshall MS 200/57, ff. 24–25, "Theory

of Wheels". Hereafter the Marshall collection at The Brotherton Library is referenced simply as Marshall MS with the appropriate number. See the following site for the handlist of the collection: http://www.leeds.ac.uk/library/spcoll/handlists/006MS200_marshalls.pdf.

8. Hannah Barker, "'Smoke cities': Northern industrial towns in late Georgian England", *Urban history*, xxxi (2004), 175–276; and for the political spokesman for this rising industrial class in Leeds see David Thornton, "Edward Baines, sr (1774–1848), provincial journalism and political philosophy in early nineteenth-century England", *Northern history*, xl (2003), 277–97.
9. Boulton and Watt MSS, Birmingham City Library, Series I, Part 3 for extensive lists of steam engines being installed in the county of York from the 1780s onward, P6; *cf.* Series I, Part 7, Box 322, Reel 97, #79, Boulton in Leeds writing to Watt in Birmingham, 24 April 1802: "At Manchester the increase of Mills and Dwelling Houses is beyond all former times, not less than 8 to 10 thousand in the last two years. Everywhere full employment and great plenty. Hull is increasing rapidly, where they are beginning a new Dock. At York I do not observe the smallest change."
10. For a good overview of the period see E. J. Connell and M. Ward, "Industrial development, 1780–1914", in Derek Fraser (ed.), *A history of modern Leeds* (Manchester, 1980), 142–76.
11. See Jacob and Reid, *op. cit.* (ref. 1), on Manchester. See also Benjamin Silliman, *Journal of travels in England, Holland and Scotland*, 3rd edn (New Haven, 1820 [orig. pub. 1809]), 99, praising Manchester's patronage of science: "It is no small gratification to find a taste for science in a great manufacturing town, where the acquisition of property is the very business of life."
12. We now know that the town possessed boarding schools for boys — as early as 1769 — that offered accounting, arithmetic, geometry, trigonometry and "the doctrine on mechanics with the theory and application of the mechanic powers". See advertisements in the *Leeds Mercury*, 3 January 1769, 16 January 1770. There was a Commercial and Mathematical School on Boar Lane that taught natural philosophy in the late 1780s. In 1788 a Mr Burton gave a course for men and women in natural and experimental philosophy endorsed by Joseph Priestley. There is a flyer for the course housed at the Education Library, Hillary Place, Leeds, and I wish to thank its librarian Liz Lister for this information.
13. Bouton and Watt Papers, Series 1, Part 7, Box 322, Reel 97, Boulton to Watt, Leeds, 28 January 1794: "From the general success of Mess. Wormald & Co's great Engine — I have no doubt of several others being wanted here if business mends on a similar plan as they are endeavouring to manufacture from the wool to finished cloth in the one building — which has not yet been done to any great extent. It caused a great bustle among the cloth makers who wish if possible to prevent it as they say merchants is becoming manufacturers. The cloth makers are a large body of men who all bring their cloth to a common hall for sale — each cloth maker has workmen of their own and they in general have the wool [?] (i.e. carded) at one place, spun at the other ... it is not the working men who are so much sett against it as their masters...."
14. "Thoughts on the Industrial Revolution", Jack Goldstone, George Mason University, Center for Global Policy Working Paper #2, 2005, p. 7. Here he is taking issue with the work of Nicholas Crafts and C. Knick Harley in particular.
15. Mokyr, *The gifts of Athena* (ref. 1).
16. Goldstone, *op. cit.* (ref. 14), 8.
17. Jack A. Goldstone, "Efflorescences and economic growth in world history: Rethinking the 'rise of the West' and the Industrial Revolution", *Journal of world history*, xiii (2002), 323–89, p. 334.
18. See note three and other essays in the entire issue of *Perspectives on science*, xiii/4 (2005). I have hyphenated 'techno-science' precisely to distinguish it from any effort to collapse the technology into the science or vice-versa.
19. The Brotherton Library, University of Leeds, Special Collections, MS 18, notes made by W. Lindley on a "number of steam engines engaged in the different branches of manufacture in Leeds and its immediate vicinity", March 1824, describe engines in the production of wool cloth (37), flax

spinning (23), stuff manufacture (2), cotton (2), dying (25), crushing seed (12), machine making (14), manufacturing tobacco, paper making, potteries. See also Pauline M. Litton (ed.), "The journals of Sarah Mayo Parkes, 1815 and 1818", *Publications of the Thoresby Society*, 2nd ser., xiii (Miscellany) (2003), 1–62, p. 3, where Parkes observes a water wheel used to move a hammer in Sheffield; p. 4, to dye blue woollen cloth at Wakefield, "most of the moveable apparatus is conducted by steam"; pp. 5–6, for an extensive description of the Wormald Gott factory where the steam engine "is the great moving power in this extensive factory" that employed machines to mix the wool with oil, to spin thread by steam driven machines (she claims that one man can do the work of 80); fulling "is very simple: the cloth is merely put into a wooden trough, to which two heavy wooden hammers are attached, that just fit into it, and each hammer works ... all the vats for dyeing the cloth are boiled by steam, which save much expence and labour". In Leeds (p. 13) she sees coal carriages moved by steam; p. 16 on woollen cloth dressed by machinery moved by steam.

20. Robert Beatson, *An essay on the comparative advantages of vertical and horizontal wind-mills: containing a description of an horizontal wind-mill and water-mill, upon a new construction* (London and Edinburgh, 1798), 3–4.
21. That could be extrapolated out of Arnold Thackray, "Natural knowledge in cultural context: The Manchester mode", *American historical review*, lxxiv (1974), 672–709.
22. For a general account of the Mechanics' Institutes in Britain, see Ian Inkster, "The social context of an educational movement: A revisionist approach to the English mechanics' institutes, 1820–1850", in his *Scientific culture and urbanisation in industrialising Britain* (Ashgate, 1997).
23. See for example, Rev. S. Vince, *A plan of a course of lectures on the principles of natural philosophy* (Cambridge, 1793), 40, "The friction of a body does not continue the same when it has different surfaces applied to the plane on which it moves, but the smallest surface will have the least friction." The British Library copy owned by Thomas Barber in 1800 (#1600/1154) has the following note: "some writers have asserted that friction is increased in the same body if its velocity be increased, but this is not the case, as appears from Mr. Vince's Experiments." Found in the blank sheets after p. 44.
24. This phrase appears widely in the older literature but can be most readily accessed in Peter Mathias, "Who unbound Prometheus?", in Peter Mathias (ed.), *Science and society 1600–1900* (Cambridge, 1972).
25. John Smail (ed.), *The memorandum books of John Brearley* (Woodbridge, Suffolk, 2001), 13. See pp. 58–60 for Brearley's knowledge of pulleys, Archimedes screws; entries here cited range from 1758 to 1761.
26. A superb example of the kind of person I mean is found in John Smail, "Innovation and invention in the Yorkshire wool textile industry: A miller's tale", in Liliane Hilaire-Pérez and Anne-Françoise Garçon (eds), *Les chemins de la nouveauté: Innover, inventer au regard de l'histoire* (Paris, 2003), 313–29. *Cf.* for a good description of the millwright of the mid-eighteenth century D. T. Jenkins, *The West Riding wool textile industry 1770–1835* (Pasold Research Fund Ltd (U.K.), 1975), 101–2, quoting Fairbairn.
27. An argument documented in my *Scientific culture* (ref. 1), and with Larry Stewart, *Practical matter* (ref. 1).
28. John Desaguliers, *A course of experimental philosophy*, 2nd edn, i and ii (London, 1745); John Smeaton, "An experimental examination of the quantity and proportion of mechanic power necessary to be employed in giving different degrees of velocity to heavy bodies from a state of rest", *Philosophical transactions of the Royal Society*, xlvi (London, 1777), 450–75; The John Rylands Library, Dalton MSS, no. 83, lecture notes dating from 1796 to 1818.
29. Marshall MSS, MS 200/57, dated 1790, ff. 34–35: Bobbin, "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.... The central force being likewise in proportion to the quantity of matter, a bobbin of the size above described which would not spin 16 lea yarn at a greater velocity than 2000 revs. Would spin 36 lea yarn at a velocity of 3000 revs. A min. In that case the 36 lea ought to be of equal strength with the 16 lea, otherwise it would break the oftener." Folio 36 has the date of 1805.

30. A similar transition in educational level has been argued for 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". See Philip Scranton, "Learning manufacture: Education and shop-floor schooling in the family firm", *Technology and culture*, xxvii (1986), 40–62, p. 46. To see a working engine recreated with its moving parts, http://www.sciencemuseum.org.uk/on-line/energyhall/theme_See%20the%20engines%20at%20work.asp.

31. William Turner, *A general introductory discourse, delivered, on Tuesday, Nov. 16, 1802 on the ... plan of the new institution for public lectures on Natural Philosophy*, Newcastle, [1802], 19–20, where it is also stated that one course will comprise "the history and exhibition of the best Machines dependent on these principles". *Cf.* John Banks, *A treatise on mills* (London, 1795) and his *On the power of machines* (Kendal, 1803).

32. Here is Watt describing the operation of one of his engines in a Cornish mine, and I quote from a printed quarto sheet, late eighteenth century, entitled *PROPOSALS to the Adventurers,* Boulton and Watt. The original can be found at http://www.cornish-mining.org.uk/mintech/boulton_watt/volume11.htm, citation number AD1583/11/66, *Method of Calculating tables for Wheal Maid 63 inch Cylinder; double 9 feet or 18 feet Stroke*:

> The consumption by cylinders of different diameters, loaded to the same number of pounds per inch, going the same number and length of strokes per minute, and constructed equally well, will be as the square of their diameters.
>
> V. The two engines at Poldice consume 6924 bushels in 30 days; the squares of their diameters (60 and 66) are 3600 and 4356; the sum of these squares is 7956. To find the consumption of a 60 inch loaded to the average of these two, say, as 7956 (sum of the squares) is to 6924 bushels, so is 3600 (square 60) to 3131, the bushels which would be consumed in 30 days by a 60 inch cylinder, going six strokes per minute of five feet six inches long each, and loaded to 5, 4-10ths pounds per square inch.

For Watt's scientific and technical education see Birmingham City Library, James Watt Papers, BPL, MS4/11, letters to his father, 1754–74.

33. Leeds University, The Brotherton Library, Special Collections, MS 18, "Number of steam engines engaged in the different branches of manufacture in Leeds and its immediate vicinity, from a survey of them made by W. Lindley in March 1824". In 1851 at the Great Exhibition Leeds sent 134 exhibitors, led only by Manchester with 191, while Birmingham put forward a huge 230.

34. Litton (ed.), *op. cit.* (ref. 19), 16.

35. Quoted in R. J. Morris, "The rise of James Kitson: Trade union and the Mechanics Institution, Leeds, 1826–1851", *Publications of the Thoresby Society*, xv (1972), 185–6. See the original in Frederic Hill, *National education: Its present state and prospects* (London, 1836), ii/2, 220–1.

36. See *The tenth report of the Keighley Mechanics' Institution, for the year ending April 4th, 1836 with a list of the members, a catalogue of the books and apparatus* (Keighley, 1836); this printed catalogue turns up in The Brotherton Library, Leeds University, Special Collections, Marriner MS 65/1. The institute was founded in 1825 and at times struggled.

37. [Anon.], *Observations on woollen machinery* (Leeds, 1803), 4; reproduced in *The spread of machinery: Five pamphlets 1793–1806* (New York, 1972).

38. Marshall's rise is ably chronicled in W. G. Rimmer, *Marshalls of Leeds, flax-spinners 1788–1886* (Cambridge, 1960); and see H. Heaton, "Benjamin Gott and the Industrial Revolution in

Yorkshire", *The economic history review*, iii (1931–32), 45–66, pp. 52–53. Rimmer did not explore in any detail the linkage between the natural philosophical and chemical work undertaken by Marshall and his industrial practices. He did recognize that Marshall had a serious interest in chemistry (pp. 50–53); he also missed the important 1790 notebook. The electronic version of the British archival guide [A2A] simply picks up the typing error in the original and lists it as from 1750; in January 2006 the entry for MS 200/42 can be found under "Booth".

39. *The Leeds Intelligencer*, xxxviii, no. 1894 (14 December 1790), tells us that "Booth's course of lectures on natural and experimental philosophy, astronomy, chemistry ... illustrated by ... apparatus, which has cost upwards of four thousand pounds ... will consist of 15 lectures at the cost of one guinea, 3 lectures a week, will begin if 40 subscribers can be found ... his apparatus weighs up to 7 tons ... he can only give one course as he has obligations in Birmingham ... subscriptions can be had from him or at the bookstore of Mr Binns". There was a John Booth who also lectured in Yorkshire in this period but there is no evidence that he was a follower of Priestley — as was this Mr Booth — nor did he announce or advertise any lectures at the time when Marshall attended them.
40. Marshall MS 200/42, "Philosophical Lectures and Extracts", Booth's Philosophical Lectures December 1790, Lecture 14, Miscellany, "Some particulars relating to various subjects which were before omitted. Water Wheels Steam Engines".
41. Eric Robinson, "An English Jacobin: James Watt, Junior, 1769–1848", *Cambridge historical journal*, xi (1955), 349–55, pp. 354–5, mentions that Benjamin Booth, itinerant lecturer, was also brought up on charges of sedition as was Thomas Walker in 1792–93; Booth was later released.
42. On the family's association with Mill Hill see Rimmer, *Marshalls of Leeds* (ref. 38), 14. For background on this Unitarian link to science see Jean Raymond and John V. Pickstone, "The natural sciences and the learning of the English Unitarians", in Barbara Smith (ed.), *Truth, liberty, religion: Essays celebrating two hundred years of Manchester College* (Oxford, 1986), 127–64, pp. 134–5. On Priestley in Leeds see Robert E. Schofield, *The Enlightenment of Joseph Priestley: A study of his life and work from 1733 to 1773* (University Park, PA, 1997), chaps. 7–11.
43. The Institution of Civil Engineers, London, MS Society of Civil Engineers, Treasurer's minutes and accounts, 1793–1821, meeting record of "Smeatonians"; and The Brotherton Library, Leeds University, Special Collections, MS 194/14.
44. See my *Scientific culture* (ref. 1), chap. 5.
45. *The Leeds Intelligencer*, xxxviii, no. 1894 (14 December 1790). This Mr. Booth could be the same Benjamin Booth, labelled as "a labourer" in John Barrell, *Imagining the King's death: Figurative treason, fantasies of regicide 1793–9* (Oxford, 2000), 171–9.
46. Birmingham City Library, James Watt MSS, Smeaton to Boulton and Watt, 5 February 1778. *Cf.* "A small working model of a steam-engine all in brass ... £23 2s. 0d" and "A Complete copy of Boulton & Watts most improved engine with the boiler and apparatus complete ... £100", found in *A catalogue of optical, mathematical, and philosophical instruments*, *made and sold by W. and S. Jones, Lower Holborn* (London, 1837), 13; in British Library copy bound with C. H. Wilkinson, *An analysis of a course of lectures on the principles of natural philosophy* (London, 1799). There is some suggestion that as early as the 1730s Desaguliers was building models at home; see Larry Stewart, *The rise of public science: Rhetoric, technology, and natural philosophy in Newtonian Britain, 1660–1750* (Cambridge, 1992), 229.
47. Victoria and Albert Museum, London, model of a rotative steam engine, about 1800; mahogany frame with brass and iron fittings. Scale 1:12; made in Britain by an unidentified modelmaker; height: 93.5 × width: 90 × depth: 41.6 inches. This model is similar to the early rotative steam engines first developed by James Watt (1736–1819) and Matthew Boulton (1728–1809) in the 1780s. It was made by an unidentified engineering apprentice in about 1800.
48. Thomas Young, *A course of lectures on natural philosophy and the mechanical arts (*London, 1807),

plate 24.

49. A. Walker, *Analysis of a course of lectures in natural and experimental philosophy*, 11th edn (London, [1799]). F. Hardie tells us that he too had apparatus at his experimental philosophic lecture room that could be seen for a shilling: F. Hardie, *Syllabus of a course of lectures ... at his experimental philosophic lecture room and theatre of rational amusement, Pantheon, Oxford St., London* (London, [1800]), statement from the title page. The advertisement on the back page for Adam Walker's lectures in March says that he will devote one lecture to hydrostatics and hydraulics with the Boulton & Watt engine figuring prominently.
50. *The Leeds Intelligencer*, xxxviii, no. 1894 (14 December 1790). The advertisement a week later says that "he cannot do it for less than 40 people". On Dec. 28 we are told that the lectures will commence in the ensuing week, 2 nights a week in Mr Hodgson's large room at the Academy. The first week will present pneumatics then hydrostatics.
51. I owe this point to Larry Stewart, "Laboratory spaces and industrial practice, 1750–1800", unpublished paper delivered to the History of Science Society annual meeting, Minneapolis, November 2005.
52. Dalhousie University, Halifax, Dinwiddie MS 2-276, notebook entitled "Mechanics", n.f.**,** dated 9 June 1787, where he tells us that he watched at the Royal Society "a new method for converting a circular into a reciprocating motion". Made available through the generosity of Larry Stewart.
53. All these notes and experiments are contained in sections of MS 2-276 labelled "experiments" and "instruments".
54. Another point owed to Larry Stewart, citing Richard Watson, *Chemical essays* (Cambridge, 1781), ii, 39–40.
55. Marshall MS 200/53, "Experiments on spinning tow from June to October 1788", nos. 1–17, not foliated; for example, "From the above experiment it appears that flax will not spin with rollers the common way because the fibers will not stick together so much as to hand forward from one roller to another especially at such distances as the length of the fiber requires them to be. It will be spun best from a sliver drawn from the heckle after the same manner as worsted if that be practicable". The trial and error work of Matthew Murray is noted here throughout. See also MS 200/55, vol. i, "Bleaching", which contains Marshall's notes on every major chemist of the day, but frequently without book or page cited: Berthollet, *Encyclopédie méthodique*, Ainsworth, Lavoisier. In a note dated 1800 we find an account of Chaptal's vapour bleaching; f. 2 recounts Berthollet's method of bleaching by oxygenated muriatic acid, translated, we are told, in the Repertory of Arts from the *Annales de chimie*: "when it has spent its power, it is common muriatic acid, the coloring particles having taken away its oxygen." For the next generation and similar notations see Marshall MS 200/31, I (someone has written that this appears to be in the hand of John Marshall) and II, 30 October 1825, "Proposed experiments during James's absence". Notes on Marshall's chemical reading also found in MS 200/42 and include notes on Scheele's *Chemical essays*, p. 92; Waltin's Chemical Lectures 1804 [name could be Martin], agriculture; a note on Stonehenge as an ancient observatory; from Leslie on Heat 8vo – 1804, "Light is heat in a state of emission", "The same portion of heat raises the temperature of ice 10 degrees, water 9, steam 572 [?]"; Dr Moyle's lectures 1805 on the atmosphere, lightening, rivers, the ocean; a section labelled <u>geology</u>, <u>combustible fossils</u>; a note stating that a grain of hydrogen explodes with a force of 500 TT [? tons]; notes labelled <u>Leslie on Heat</u> 8vo. 1804; then notes on various books about travel. Also present are notes on an item in the *Phil. trans.* on geology and archaeology of Lincolnshire; notes on the sea at the equator and its elevation; South America; <u>Coal</u>; Hutton's theory on formation of peat. Further notes are on Bruce vol. 3; Helm's travels in south America; 1809 Barrow's voyage to China; De Luc's *Elements of geology*, 1809; Cuvier as discussed in the *Edinburgh Review*, 1811.
56. For a list of Dalton's lectures see Arnold Thackray, *John Dalton: Critical assessments of his life and*

science (Cambridge, MA, 1972), 108–12, which in 1805 included lectures on matter, motion and mechanic principles; hydrostatics, pneumatics, as well as hydraulic and pneumatic instruments; electricity and galvanism, magnetism, optics, etc. There were also lectures on mixed elastic fluids and the atmosphere that ended with astronomy, the solar system, eclipses, laws of motion of the planets explained by the whirling table, tides, and system of the universe.

57. Marshall MS 200/42, "Philosophical Lectures and Extracts, Booth's Philosophical Lectures, December 1790", from Lecture 1.
58. *Ibid*. This manuscript is not foliated.
59. *Ibid.*
60. *Ibid*., Lecture 2.
61. *Ibid*., Lecture 5 on hydraulicks.
62. *Ibid*., Lecture 5, "3. In the clack or valve ... the very best possible construction is the mitre clack — a working model of Dr. Franklin's contrivance for drawing water by a hair rope was exhibited & proved not to answer — a model of a pump invented by Mr Booth was shewn which pumped the water by a continued circular motion. A model of a pump which made a stroke drained water both by the piston's ascending & descending — a model of a machine for raising a quantity of water 3 feet high by means of a small stream of water equal to 78 [?] of the water raised falling 30 feet ... the piece of wood then falls to the bottom & raises a quantity of water equal to its own weight at the other end of a beam" and on the next page, "Newton attributed the tide on the opposite side of the earth from the moon to the solid part of the earth being more attracted than the water on the opposite side & being as it were drawn away from it. Ferguson ascribes it to the centrifugal force arising from the earth's moving round its common center of gravity with the moon. That center of gravity is abt 2000 miles from the surface of the earth". In discussing valve of the pump he notes that vibration decreases velocity. Lecture 10 is on pneumatick chemistry with a long discussion of phlogiston theory and its errors. Lectures 11 and 12 are on electricity: "electric matter is a fluid sui generis — it follows the law of all other fluids in endeavouring to keep up an equilibrium in all its parts — all bodies more or less contain a portion of this matter & that portion may be increased or diminished." Then Dr Moyes on Electricity — applications are discussed and these are entirely medical; also how to deploy lightening rods to protect a house, proper distance between the rods, etc.
63. *Ibid*., Lecture 5 on hydraulicks.
64. *Ibid*., Lecture 13.
65. *Ibid*., "From Leslie on Heat 8vo — 1804 Light is heat in a state of emission. The same portion of heat raises the temperature of ice 10 degrees, water 9, steam 572 [? Symbol unclear]".
66. Marshall MS 200/57, Notebook *c*. 1790, opening pages list all items alphabetically. Folio 1 is entitled "Steam Engine" and gives a list of engines at work in the region with all of their specifics and the list is continued on f. 27; undated, these pages including some engines in Manchester; f. 2–27 cited in ref. 7. In ff. 6–7 we have lists of names of Mechanicks, e.g., Joshua Wrigley, erector of Steam Engine & Cotton Machinery – Man [Manchester]; then spindle makers, steel burners, roller makers.
67. Rimmer, *Marshalls of Leeds* (ref. 38), 125.
68. Marshall MS 200/57, Notebook *c*. 1790, f. 38 labelled Strength of wheels, "To find the strength necessary for any given power — Rule The square of the thickness..." and cited in ref. 7.
69. *Ibid*., f. 17 labelled Speed: "the greatest speed at which they can spin cotton is 15ft a min. or 12 feet a min the day through including stoppages."
70. Marshall MS 500/57, Notebook *c*. 1790, ff. 24–25. See similar points being made by Rev. S. Vince, *A plan of a course of lectures on the principles of natural philosophy* (Cambridge, 1793), 40: "The friction of a body does not continue the same when it has different surfaces applied to the plane on which it moves, but the smallest surface will have the least friction." In a British

Library copy of Vince's book, owned in 1800 by Thomas Barber of Cambridge (call number 1600/1154), the student's ms notes read in part "Some Writers have asserted that Friction is increased in the same body if its velocity be increased, but this is not the case, as appears from Mr Vince's Experiments", found in blank sheets after p. 44.

71. Marshall MS 200/57, ff. 34–35. Here we find notations on 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." The same is found in Vince, *op. cit*. (ref. 70), 7. These lectures concerned in this order: mechanics, hydrostatics, optics, magnetism, and astronomy.
72. Vince, *op. cit.* (ref. 70), 9: "In a fixed pulley, the power is equal to the weight."
73. Marshall MS 200/57, Notebook, dated 1790, but notes continue in later years, and this one on f. 36 is dated 1805.
74. Cited in Rimmer, *Marshalls of Leeds* (ref. 38), 29.
75. *Ibid*., 32, from Marshall's ms notebook, "experiments". See also MS 200/53, "experiments on spinning tow from June to October 1788".
76. *The repertory of arts and manufactures: consisting of original communications, specifications or patent inventions...*, xi (London, 1799), 309–14. I owe this reference to Murray's work to Larry Stewart.
77. As cited in ref. 7, Marshall MS 200/57, f. 38, on the breadth of the tooth.
78. Marshall MS 200/55, f. 2. For a similar discussion of oxygenated muriatic acid see William Nicholson, *A dictionary of chemistry* (London, 1795), 209, entry under bleaching of linens.
79. Marshall MS 200/55, f. 21, March 1798, "we began to try experiments with the bleaching liquor ... after procedures done first by Ainsworth working on cotton". Discussed briefly in Rimmer, *Marshalls of Leeds* (ref. 38), 52.
80. Marshall MS 200/55, ff. 63–64.
81. Marshall MS 200/31 (I), and (II), f. 15.
82. The Brotherton Library, Gott MSS, MS 193/2, letters from Boulton & Watt, Peter Ewart, James Lawson, John Rennie; MS 193/74–84, copies of letters from Boulton & Watt that are now housed at the Birmingham City Library and are also available on microfilm.
83. Gott MSS, MS 193/3, f. 98, letter of 5 May 1802, from Davison to Gott asking him if he would give him an opinion of his steam engine.
84. Gott MSS, MS 117, Bean Ing Mill Notebook of Prices and Processes [*c*. 108–25], "experiments made in the Dye house Park Mill, 9 Sept. 1800".
85. Gott MSS, MS 193/3, f. 98, letter of Davison to Gott, 5 May 1802, asking him if he would go with him to give his opinion of their steam engine to Goodwin, "but if you can't here are queries in writing". On the engine and its many uses for scribbling, carding, turning shafts and gearings, and stones to grind dyewood, see Heaton, *op. cit.* (ref. 38), 52–53.
86. Gott MSS, MS 193/3, f. 97, Gott to Bramah, 29 March 1809.
87. Gott MSS, MS 193/3, f. 94.
88. *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, *op. cit.* (ref. 38), 58 who takes a dimmer view of Gott's success in putting the machine to work.
89. Gott MSS, MS 193/3, f. 98, letter of 5 May 1802, Davison to Gott.

90. Leeds University, The Brotherton Library, Special Collections, MS Dep. 1975/1/6, 7 May 1819.

91. Charles Thackrah, *An introductory discourse. Delivered to the Leeds Philosophical and Literary Society, April 6, 1821* (Leeds, 1821), 23–24.

92. Marshall MS 200/63, unfoliated. For their knowledge of the Lake District and the relationship between Jane Marshall and Dorothy Wordsworth, see Ernest de Selincourt (ed.), *The letters of William and Dorothy Wordsworth*, 2nd edn rev. by Chester L. Shaver, i: *The early years, 1787–1805* (Oxford, 1967).

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