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The Nature of Industrial Revolution

In the eighteenth century, a series of inventions transformed the British cotton manufacture and gave birth to a new mode of production—the factory system.* At the same time, other branches of industry made comparable and often related advances, and all of these together, mutually reinforcing, drove further gains on an ever-widening front. The abundance and variety of these innovations almost defy compilation, but they fall under three principles: (1) the substitution of machines—rapid, regular, precise, tireless—for human skill and effort; (2) the substitution of inanimate for animate sources of power, in particular, the invention of engines for converting heat into work, thereby opening an almost unlimited supply of energy; and (3) the use of new and far more abundant raw materials, in particular, the substitution of mineral, and eventually artificial, materials for vegetable or animal substances.

These substitutions made the Industrial Revolution. They yielded a rapid rise in productivity and, with it, in income per head. This growth,

moreover, was self-sustaining. In ages past, better living standards had always been followed by a rise in population that eventually consumed the gains. Now, for the first time in history, both the economy and knowledge were growing fast enough to generate a continuing flow of improvements. Gone, Malthus's positive checks and the stagnationist predictions of the "dismal science"; instead, one had an age of promise and great expectations. The Industrial Revolution also transformed the balance of political power—within nations, between nations, and between civilizations; revolutionized the social order; and as much changed ways of thinking as ways of doing.

The word "revolution" has many faces. It conjures up visions of quick, even brutal or violent change. It can also mean fundamental or profound transformation. For some, it has progressive connotations (in the political sense): revolutions are good, and the very notion of a reactionary revolution, one that turns the clock back, is seen as a contradiction in terms. Others see revolutions as intrinsically destructive of things of value, hence bad.

All of these and other meanings hang on a word that once meant simply a turning, in the literal sense. Let me be clear, then, about the way I use the term here. I am using it in its oldest metaphorical sense, to denote an "instance of great change or alteration in affairs or some particular thing"—a sense that goes back to the 1400s and antedates by a century and a half the use of "revolution" to denote abrupt political change.[1] It is in this sense that knowing students of the Industrial Revolution have always used it, just as others speak of a medieval "commercial revolution" or a seventeenth-century "scientific revolution" or a twentieth-century "sexual revolution."

The emphasis, then, is on deep rather than fast. It will surprise no one that the extraordinary technological advances of the great Industrial Revolution (with capital I and capital R) were not achieved overnight. Few inventions spring mature into the world. On the contrary: it takes a lot of small and large improvements to turn an idea into a technique.

Take steampower. The first device to use steam to create a vacuum and work a pump was patented in England by Thomas Savery in 1698; the first steam engine proper (with piston) by Thomas Newcomen in 1705. Newcomen's atmospheric engine (so called becuase it relied simply on atmospheric pressure) in turn was grossly wasteful of energy because the cylinder cooled and had to be reheated with every stroke. The machine therefore worked best pumping water out of coal mines, where fuel was almost a free good.

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* By *factory* is meant a unified unit of production (workers brought together under supervision), using a central, typically inanimate source of power. Without the central power, we have a *manufactory*.

A long time—sixty years—passed before James Watt invented an engine with separate condenser (1768) whose fuel efficiency was good enough to make steam profitable away from the mines, in the new industrial cities; and it took another fifteen years to adapt the machine to rotary motion, so that it could drive the wheels of industry. In between, engineers and mechanics had to solve an infinitude of small and large problems of manufacture and maintenance. The task, for example, of making cylinders of smooth and circular cross section, so that the piston would run tight and air not leak to the vacuum side, required care, patience, and ingenuity.* In matters of fuel economy, every shortcoming cost, and good enough was not good enough.

~~That was not all. Another line remained to be explored: high-pressure engines (more than atmospheric), which could be built more compact and used to drive ships and land vehicles. This took another quarter century. Such uses put a premium on fuel economy: space was limited, and one wanted room for cargo rather than for coal. The answer was found in compounding—the use of high-pressure steam to drive two or more pistons successively; the steam, having done its work in a high-pressure cylinder, expanded further in a larger, lower-pressure cylinder. The principle was the same as that developed in the Middle Ages for squeezing energy out of falling water by driving a series of wheels. Compounding went back to J. C. Hornblower (1781) and Arthur Woolf (1804); but it did not come into its own until the 1850s, when it was introduced into marine engines and contributed mightily to oceanic trade.~~

Nor was that the end of it. The size and power of steam engines were limited by the piston's inertia. Driving back and forth, it required enormous energy to reverse direction. The solution was found (~~Charles A. Parsons~~, 1884) in converting from reciprocating to rotary motion, by replacing the piston with a steam turbine. These were introduced into central power plants at the very end of the nineteenth century; into

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* The technique that worked for boilers (roll up a sheet, weld the seams, and cap top and bottom) would not work for an engine cylinder—too much leakage. The new method, which consisted in boring a solid casting, was the invention of John Wilkinson, c. 1776, who learned by boring cannon (patent of 1774). A year later, Wilkinson was using the steam engine to raise a 60-pound stamping hammer to forge heavy pieces. By 1783, he was up to 7.5 tons. With this he was soon building rolling mills, coining presses, drawing benches (for wire manufacture), and similar heavy machinery. "By a strange caprice of public fancy," writes Usher, "this grim and unattractive character has never secured the fame he deserves as one of the pioneers in the development of the heavy-metal trades." *History of Mechanical Inventions,* p. 372. Vulcan wasn't pretty either.

ships shortly after. In all, steam engine development took two hundred years.*

Meanwhile, waterpower, itself much improved (~~breast wheel [John Smeaton, 1750s~~] and turbine [~~Benoît Fourneyron, 1827~~]), remained a major component of manufacturing industry, as it had been since the Middle Ages.[2]

Similarly the first successful coke smelt of iron, by Abraham Darby at Coalbrookdale, went back to 1709. (I have stood inside the abandoned blast furnace at Coalbrookdale, there among the pitted bricks where the fire burned and the ore melted, and thought myself inside the womb of the Industrial Revolution. It is now part of an industrial museum, and curious visitors can look at it from outside.) But this achievement, though carefully studied and prepared, was in effect a lucky strike: Darby's coal was fortuitously suitable.[3] Others had less success, and they, as well as Darby, had to confine use of coke-smelted pig iron to castings. It took some forty years to resolve the difficulties, and coke smelting took off only at midcentury.

~~This technology, moreover, had serious limitations. Cast iron suited the manufacture of pots and pans, firebacks, pipes, and similar unstressed objects, but a machine technology cannot be based on castings. Moving parts require the resilience and elasticity of wrought iron (or steel) and must be shaped (forged or machined) more exactly than casting can do.† A half century and much experiment went by before ironmasters could make coke-smelted pig suited to further refining~~

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* The latter part of the nineteenth century saw substantial improvement in the steam engine thanks to scientific advances in thermodynamics. Where before technology had led science in this area, now science led and gave the steam engine a new lease on life.

On the logistic (lazy-S) curve of possibilities implicit in a given technological sequence—slow gains during the experimental preparatory stage, followed by rapid advance that eventually slows down as possibilities are exhausted—see the classic essay of Simon Kuznets, "Retardation of Industrial Growth."

† Pig (cast) iron is high in carbon content (over 4 percent). It is very hard, but will crack or break under shock. It cannot be machined, which is why it is cast, that is, poured into molds to cool to shape. Wrought iron can be hammered, drilled, and otherwise worked. It will not break under shock and is highly resistant to corrosion, which makes it ideal for balcony railings and other open-air uses (cf. the Eiffel Tower). To get from pig to wrought iron, most of the carbon has to be burned off, leaving 1 percent or less. Wrought iron has long since been replaced by steel (1 to 3 percent carbon), which combines the virtues of both cast and wrought iron, that is, hardness with malleability; as a result, wrought iron is just about unobtainable today except as scrap. The difficulty with the early coke-blast iron was that, on refining, it yielded an iron that was red-short, that is, brittle when hot. Until that problem was solved, wrought iron was made using charcoal-blast pig.

[redacted]). Cheap steel (Henry Bessemer, 1856) took another three quarters of a century. Cheap steel transformed industry and transportation. Where once this costly metal had been reserved for small uses—arms, razors, springs, files—it could now be used to make rails and build ships. Steel rails lasted longer, carried more; steel ships had thinner skins and carried more.

Moreover, if origins we seek, we can push both these technical sequences back to the sixteenth century, to the precocious reliance of English industry on coal as fuel and raw material, in glassmaking, brewing, dyeing, brick- and tilemaking, smithing and metallurgy. One scholar has termed this shift to fossil fuel, far earlier than in other European countries, a "first industrial revolution."[4]

Next, powered machinery. The machine itself is simply an articulated device to move a tool (or tools) in such wise as to do the work of the hand. Its purpose may be to enhance the force and speed of the operator as with a printing press, a drill press, or a spinning wheel. Or it may channel its tool so as to perform uniform, repetitious motions, as in a clock. Or it may align a battery of tools so as to multiply the work performed by a single motion. So long as machines are hand-operated, it is fairly easy to respond to the inevitable hitches and glitches: the worker has only to stop the action by ceasing to wind the crank or yank the lever. Power drive changes everything.*

The Middle Ages, we saw, were already familiar with a wide variety of machines—for grinding corn or malt, shaping metals, spinning yarn, fulling cloth, scrubbing fabrics, blowing furnaces. Many of these were power-driven, typically by water wheels. In the centuries that followed (1500–), these devices proliferated, for the principles of mechanics were widely applicable. In textiles, some of the important innovations were the knitting frame, the "Dutch" or "engine" loom, the ribbon loom; also powered machines for throwing silk. But the most potent advances, as is often the case, were the most banal:

—the introduction of the foot treadle to drive the spinning wheel, thereby freeing the operative's hands to manipulate the thread and deal with winding; or, for the loom, to work the headles while throwing the shuttle;

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* Power machinery was inevitably a new source of industrial accidents. On problems in the sugar mills and the greater safety of hand-operated or animal-driven devices, see Schwartz, *Sugar Plantations,* pp. 143–44. Horses were more dangerous than mules or oxen: ". . . the screams of the unfortunate slave caused the horses to run faster."

—the invention of the flyer (the Saxon wheel), which added twist by winding the yarn at the same time as it turned the spindle, but at a different speed;

—the achievement of unidirectional, continuous spinning and reeling.

These changes together quadrupled or better the spinner's productivity.[5]

The next step was to mechanize spinning by somehow replicating the gestures of the hand spinner. This required simplifying by dividing: breaking up the task into a succession of repeatable processes. That seems logical enough, but it was not easy. Not until inventors applied their devices to a tough vegetable fiber, cotton, was success achieved. That took decades of trial and error, from the 1730s to the 1760s. When power spinning came to cotton, it turned industry upside down.

In metallurgy, big gains came from substituting rotary for reciprocating motion: ~~making sheet metal by rolling instead of pounding; making wire by drawing through a sequence of ever narrower holes; making holes by drilling instead of punching; planing and shaping by lathe rather than by chisel and hammer.~~ Most important was the growing recourse to precision gauging and fixed settings. Here the clock- and watchmakers and instrument makers gave the lead. They were working smaller pieces and could more easily shape them to the high standards required for accuracy with special-purpose tools such as wheel dividers and tooth-cutters. These devices in turn, along with similar tools devised by machinists, could then be adapted to work in larger format, and it is no accident that cotton manufacturers, when looking for skilled craftsmen to build and maintain machines, advertised for clockmakers; or that the wheel trains of these machines were known as "clockwork." The repetitious work of these machines suggested in turn the first experiments in mass production based on interchangeable parts (clocks, guns, gun carriages, pulley blocks, locks, hardware, furniture).

All these gains, plus the invention of machines to build machines, * came together in the last third of the eighteenth century—a period of contagious novelty. Some of this merging stream of innovation may have been a lucky harvest. But no. Innovation was catching because the principles that underlay a given technique could take many forms, find many uses. If one could bore cannon, one could bore the cylinders of steam engines. If one could print fabrics by means of cylinders (as against the much slower block printing), one could also print wallpaper that way; or print word text far faster than by the up-and-down strokes of a press and turn out penny tabloids and cheap novels by the tens and hundreds of thousands. Similarly, a modified cotton-spinning machine could spin wool and flax. Indeed, contemporaries argued that the mechanization of cotton manufacture forced these other branches to modernize:

> . . . had not the genius of Hargreaves and Arkwright changed entirely the modes of carding and spinning cotton, the woollen manufacture would probably have remained at this day what it was in the earliest ages. . . . That it would have been better for general society if it had so remained, we readily admit; but after the improved modes of working cotton were discovered, this was impossible.[6]

And on and on, into a brave and not-so-brave world of higher incomes and cheaper commodities, unheard-of devices and materials, insatiable appetites. New, new, new. Money, money, money. As Dr. (Samuel) Johnson, more prescient than his contemporaries, put it, "all the business of the world is to be done in a new way."[7] The world had slipped its moorings.

Can one put dates to this revolution? Not easily, because of the decades of experiment that precede a given innovation and the long run of improvement that follows. Where is beginning and where end? The core of the larger process—mechanization of industry and the adoption of the factory—lies, however, in the story of the textile manufacture.* Rapid change there began with the spinning jenny of James Hargreaves (c. 1766), followed by Thomas Arkwright's water frame (1769) and Samuel Crompton's mule (1779), so called because it was a cross between the jenny and the water frame. With the mule, one could spin fine counts as well as coarse, better and cheaper than any hand spinner.

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* Core of the process: John Hicks, *A Theory of Economic History,* p. 147, and Carlo Cipolla, *Before the Industrial Revolution,* p. 291, would not agree. Hicks saw the early cotton machinery as "an appendage to the evolution of the old industry" rather than as the beginning of a new one. He thought that something like this might well have occurred in fifteenth-century Florence had waterpower been available (but Italy does have waterpower). "There might have been no Crompton and Arkwright, and still there would have been an Industrial Revolution." "Iron and coal," writes Cipolla, "much more than cotton stand as critical factors in the origins of the Industrial Revolution." Perhaps; it is not easy to order improvements by impact and significance. But I would still give pride of place to mechanization as a general phenomenon susceptible of the widest application and to the organization of work under supervision and discipline (the factory system).

Then in 1787 Edmund Cartwright built the first successful power loom, which gradually transformed weaving, first of coarse yarn, which stood up better to the to-and-fro of the shuttle, then of fine; and in 1830 Richard Roberts, an experienced machine builder, devised—in response to employer demand—a "self-acting" mule to free spinning from dependence on the strength and special skill of an indocile labor aristocracy. (The self-actor worked, but the aristocracy remained.)

This sequence of inventions took some sixty years and dominated completely the older technology—unlike the steam engine, which long shared the field with waterpower.* The new technique yielded a sharp fall in costs and prices, and a rapid increase in cotton output and consumption.[8] On this basis, the British Industrial Revolution ran about a century, from say 1770 to 1870, "the entire interval between the old order and the establishment of a fairly stable relationship of the different aspects of industry under the new order."[9]

Other specialists have adopted slightly different periodizations.[10] Whatever; we are talking about a process that took a century, give or take a generation. That may seem slow for something called a revolution, but economic time runs slower than political. The great economic revolutions of the past had taken far longer.

~~Even when one takes account of the quantitative data put forward by the practitioners of the self-proclaimed New Economic History, one still has a break in the trend of growth around 1760–70; unprecedented rates of increase; above all, the beginnings of a profound transformation of the mode of production. Technology matters. The aggregate figures show this, and elementary logic makes it clear. If one takes even the lowest estimates of increase for the latter part of the eighteenth century and extrapolates *backward*, one quickly arrives at levels of income insufficient to support life. So something had changed.~~

~~The question remains why overall growth was not faster. It is an anachronistic question that reflects the expectations of more recent~~

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* One should distinguish here between the spinning and weaving sectors of the industry. In cotton spinning, machinery simply wiped out the older hand techniques. Even the Indian spinner, working for a small fraction of English wages, had to give up in the face of machine-spun yarn. In weaving, however, the power loom took decades to reach the point where it could deal with the more delicate, high-count yarn. So the handloom weavers hung on grimly, forever reducing expectations and standard of living in the effort to stay out of the mills, until death and old age eliminated them. By the second half of the nineteenth century, even those manufacturers who had special reasons to hire handloom weavers could no longer find them. Young persons were not ready to go into a dying trade.

times—of an era of quicker, more potent innovation and leapfrog catch-up. Even so, the question is worth posing. The answer is that the Industrial Revolution was uneven and protracted in its effects; that it started and flourished in some branches before others; that it left behind and even destroyed old trades while building new; that it did not, could not, replace older technologies overnight. (Even the almighty computer has not eliminated the typewriter, let alone pen-and-paper.)[11] This is why estimates for growth in those years are so sensitive to weights: give more importance to cotton and iron, and growth seems faster; give less, and it slows down. All of this, of course, was obvious to such earlier students of technological change as A. P. Usher and J. H. Clapham. The "new economic historians" who have stressed the theme of continuity have essentially revived their work without citing them, perhaps without knowing them.*

Many of the anti-Revolutionists have also committed the sin of either-or. Their point about continuity is well taken. History abhors leaps, and large changes and economic revolutions do not come out of the blue. They are invariably well and long prepared.[12] But continuity does not exclude change, even drastic change. One true believer in the cogency of economic theory and cliometrics notes that British income per head doubled between 1780 and 1860, and then multiplied by six times between 1860 and 1990 and acknowledges that we have more here than a simple continuation of older trends: "The first eighty years of growth were astonishing enough, but they were merely a prelude."[13] To which I would add that Britain was not the most impressive performer over this long period.

The consequence of these advances was a growing gap between modern industrial countries and laggards, between rich and poor. In Europe to begin with: in 1750, the difference between western Europe (excluding Britain) and eastern in income per head was perhaps 15 percent; in 1800, little more than 20. By 1860 it was up to 64 percent; by the 1900s, almost 80 percent.[14] The same polarization, only much sharper, took place between Europe and those countries that later came to be defined as a Third World—in part because modern factory industries swallowed their old-fashioned rivals, at home and abroad.

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* Economics is a discipline that would be a science, and as everyone knows, science marches on. So away with the monographs and articles of predecessors. Hence the paradox of a discipline that would be up to date, yet is always rediscovering yesterday's discoveries—often without realizing it.

Paradox: the Industrial Revolution brought the world closer together, made it smaller and more homogenous. But the same revolution fragmented the globe by estranging winners and losers. It begat multiple worlds.

When Is a Revolution Not a Revolution?

The reliance of early students of the Industrial Revolution on the output and price data for particular industries reflected the statistical limitations of that day: that was what they had and knew to work with. The data did not let them down. They represented direct and simple returns, and where the historian had to make use of proxy measures (imports of raw cotton, for example, as stand-in for the output of cotton yarn in countries that did not grow cotton), these were good and fairly stable indicators of a narrowly defined, unambiguous reality.[15]

Beginning in the late 1950s, however, numerically minded economic historians began to construct measures of aggregate growth during the eighteenth and early nineteenth centuries. This was a natural extension of historical work on national income for more recent periods, where data were fuller and more reliable.* But as one went back in time before the systematic collection of numbers by government bureaus, such reconstructions entailed a heroic exercise of imagination and ingenuity: use and fusion of disparate figures estimated or collected at different times, for different purposes, on different bases; use of proxies justified by often arbitrary and not always specified assumptions concerning the nature of the economy; assignment of weights drawn from other contexts and periods; index problems galore; use of customary or nominal rather than market prices; interpolations and extrapolations without end, thereby smoothing and blurring breaks in trend. It will not come as a surprise, then, that these constructions have varied with

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* The model was the work done by Simon Kuznets and colleagues at the National Bureau of Economic Research. After working on U.S. data, Kuznets helped advise and finance similar projects in other countries from the 1960s. The pioneering work on British industrial output went back even further, to the calculations of Walther Hoffmann, but a fresh start began with the researches of Phyllis Deane, followed after an interval by Charles Feinstein, Nick Crafts, Knick Harley, and others.

the builder and have changed over time; that the latest estimate is not necessarily better than the one before (the estimators would not agree); and that the appearance of precision is not an assurance of robustness or a predictor of durability.*

Neither is the appearance of precision an unambiguous indicator of meaning. Believe the data; the interpretation remains a problem. Theoretical economists have long appreciated this difficulty. Here is one "Nobéliste" who puts the matter with disarming frankness: "Early economists were not inundated with statistics. They were spared the burden of statistical proof. They relied on history and on personal observations. Now we place our trust in hard data provided they are sanctioned by theory."[16] In the light of this principle, the least one might expect of economic historians is that they put their trust in "hard [read: numerical] data" provided they are sanctioned by historical evidence. Instead, their leap to judgment often beggars credulity.

The crux of disagreement in this instance has been what has been presented by some as an unrevolutionary ("evolutionary") revolution. However impressive the growth of certain branches of production, the overall performance of the British economy (or British industry) during the century 1760–1860 that emerges from some recent numerical exercises has appeared modest: a few percent per year for industry; even less for aggregate product. And if one deflates these data for growth of population (so, income or product per head), they reduce to 1 or 2 percent a year.[17] Given the margin of error intrinsic to this kind of statistical manipulation, that could be something. It could also be nothing.

But why believe the estimates? Because they are more recent? Because the authors assure us of their reliability? The methods employed are less than convincing. One starts with the aggregate construct (figment) and then shoehorns the component branches to fit. One recent exercise found that after adding up British productivity gains in a few major branches—cotton, iron, transport, agriculture—no room was left for further gains in the other branches: other textiles, pottery, paper, hardware, machine building,

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* On the weaknesses and pitfalls of these quantitative elucubrations, see Hoppit, "Counting the Industrial Revolution," who cites (p. 189) Thomas Carlyle on the subject: "There is, unfortunately, a kind of alchemy about figures which transforms the most dubious materials into something pure and precious; hence the price of working with historical statistics is eternal vigilance." So, mid-nineteenth century and already disillusioned.

clocks and watches. What to do? Simple. The author decided that most British industry "experienced low levels of labor productivity and slow productivity growth—it is possible that there was virtually no advance during 1780–1860."[18] This is history cart before horse, results before data, imagination before experience. It is also wrong.

What is more, these estimates, based as they are on assumptions of homogeneity over time—iron is iron, cotton is cotton—inevitably underestimate the gain implicit in quality improvements and new products. How can one measure the significance of a new kind of steel (crucible steel) that makes possible superior timekeepers and better files for finishing and adjusting machine parts if one is simply counting tons of steel? How appreciate the production of newspapers that sell for a penny instead of a shilling thanks to rotary power presses? How measure the value of iron ships that last longer than wooden vessels and hold considerably more cargo? How count the output of light if one calculates in terms of lamps rather than the light they give off? A recent attempt to quantify the downward bias of the aggregate statistics on the basis of the price of lumens of light suggests that in that instance the difference between real and estimated gains over two hundred years is of the order of 1,000 to 1.[19]

In the meantime, the new, quantitative economic historians ("cliometricians") have triumphantly announced the demolition of doctrine received. One economic historian has called in every direction for abandonment of the misnomer "industrial revolution," while others have begun to write histories of the period without using the dread name—a considerable inconvenience for both authors and students.[20] Some, working on the border between economic and other kinds of history or simply outside the field, have leaped to the conclusion that everyone has misread the British story. Britain, they would have us believe, never was an industrial nation (whatever that means); the most important economic developments of the eighteenth century took place in agriculture and finance, while industry's role, much exaggerated, was in fact subordinate.[21] And some have sought to argue that Britain changed little during these supposedly revolutionary years (there went a century of historiography down the drain), while others, acknowledging that growth was in fact more rapid, nevertheless stressed continuity over change. They wrote of "trend growth," or "trend acceleration," and asserted that there was no "kink" in the factitious line that traced the increase in national product or income. And when some scholars

quant. econom history

~~refused to adopt this new dispensation, one historian dismissed them as "a dead horse that is not altogether willing to lie down."[22]~~

~~Who says the ivory tower of scholarship is a quiet place?~~

The Advantage of Going Round and Round

Rotary motion's great advantage over reciprocating motion lies in its energetic efficiency: it does not require the moving part to change direction with each stroke; it continues round and round. (It has of course its own constraints, arising largely from centrifugal force, which is subject to the same laws of motion.) Everything is a function of mass and velocity: work slowly enough with light equipment, and reciprocating motion will do the job, though at a cost. Step up to big pieces and higher speeds, and reciprocating motion becomes unworkable.

Nothing illustrates the principle better than the shift from reciprocating to rotary steam engines in steamships. Both merchant marines and navies were pressing designers and builders for ever larger and faster vessels. For Britain, the world's leading naval power, the definitive decision to go over to the new technology came with the building of *Dreadnought,* the first of the big-gun battleships. This was in 1905. The Royal Navy wanted a capital ship that could make 21 knots, a speed impossible with reciprocating engines. Although earlier vessels had been designed for 18 or 19 knots, they could do this only for short periods; eight hours at even 14 knots, and the engine bearings would start heating up and breaking down. A hard run could mean ten days in port to readjust—not a recipe for combat readiness.

Some of the naval officers were afraid to take chances with the new technology. It was one thing to use turbines on destroyers, but on the Navy's largest, most powerful ship!? What if the innovators were wrong? Philip Watts, Director of Naval Construction, settled the issue by pointing to the cost of old ways. Fit reciprocating engines, he said, and the *Dreadnought* would be out of date in five years.

The result more than justified his hopes. The ship's captain, Reginald Bacon, who had previously commanded the *Irresistible* (the Royal Navy likes hyperbole), marveled at the difference:

> [The turbines] were noiseless. In fact, I have frequently visited the engine room of the *Dreadnought* when at sea steaming 17 knots and have been unable to tell whether the engines were revolving or not. During a full speed run, the difference between the engine room of the *Dreadnought* and that of the *Irresistible* was extraordinary. In the *Dreadnought*, there was no noise, no steam was visible, no water or oil splashing about, the officers and men were clean; in fact, the ship to all appearances might have been in harbor and the turbines stopped. In the *Irresistible*, the noise was deafening. It was impossible to make a remark plainly audible and telephones were useless. The deck plates were greasy with oil and water so that it was difficult to walk without slipping. Some gland [valve] was certain to be blowing a little which made the atmosphere murky with steam. One or more hoses would be playing on a bearing which threatened trouble. Men constantly working around the engine would be feeling the bearings to see if they were running cool or showed signs of heating; and the officers would be seen with their coats buttoned up to their throats and perhaps in oilskins, black in the face, and with their clothes wet with oil and water.[23]

The next step would be liquid fuel, which burned hotter, created higher pressures, and drove shafts and propellers faster. The older coal bins took up too much space, and the stokers ate huge amounts of bulky food—human engines also need fuel. As coal stocks fell, more men had to be called in to shovel from more distant bunkers to those closer to the engines: hundreds of men never saw the fires they fed. In contrast, refueling with oil meant simply attaching hoses and a few hours of pumping, often at sea; with coal, the ship had to put into port for days.

Incidentally, much of this improvement would not be captured by the conventional measures of output and productivity. These would sum the cost of the new equipment, but not the change in the quality of work.