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Winners and Losers: The Balance Sheet of Empire

> The discovery of America, the rounding of the Cape, opened up fresh ground for the rising bourgeoisie. The East-Indian and Chinese markets, the colonisation of America, trade with the colonies, the increase in the means of exchange and in commodities generally, gave to commerce, to navigation, to industry, an impulse never before known, and thereby, to the revolutionary element in the tottering feudal society, a rapid development.
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> —MARX and ENGELS, *Manifesto of the Communist Party*

The turn of the eighteenth century was both end and beginning. It saw the liquidation of the Dutch East India Company; the prohibition of the British Atlantic slave trade (but not the end of slavery);* the peak and decline of the sugar bonanza (including revolution and the fall of planters and plantations in Saint-Domingue [now Haiti]); an end to the Old Regime in France; an end to the period of Old Empire. The new era would see Europe lose formal control of territory overseas (Spain would be the big loser) but gain wider economic dominance. Europe would also force its way into territories previously seen as inaccessible and untouchable (China, Japan), while creating in others (India, Indonesia) a new kind of imperium in its own image.

The hinge of this metamorphosis was the Industrial Revolution, begun in Britain in the eighteenth century and emulated around the world. The Industrial Revolution made some countries richer and others (relatively) poorer; or more accurately, some countries made an industrial revolution and became rich; and others did not and stayed

* In places such as the Caribbean, however, where the pool of slaves could not maintain itself by natural reproduction, the interdiction of fresh supplies would kill the old plantation system.

poor. This process of selection actually began much earlier, during the age of discovery.

For some nations, Spain for example, the Opening of the World was an invitation to wealth, pomp, and pretension—an older way of doing things, but on a bigger scale. For others, Holland and England, it was a chance to do new things in new ways, to catch the wave of technological progress. And for still others, such as the Amerindians or Tasmanians, it was apocalypse, a terrible fate imposed from without.

The Opening brought first an exchange—the so-called Columbian exchange—of the life forms of two biospheres. The Europeans found in the New World new peoples and animals, but above all, new plants—some nutritive (maize [Indian corn], cocoa [cacao], potato, sweet potato), some addictive and harmful (tobacco, coca), some industrially useful (new hardwoods, rubber). These products were adapted diversely into Old World contexts, some early, some late (rubber does not become important until the nineteenth century).

The new foods altered diets around the world. Corn, for example, became a staple of Italian (polenta) and Balkan (mamaliga) cuisines; while potatoes became the main starch of Europe north of the Alps and Pyrenees, even replacing bread in some places (Ireland, Flanders). So important was the potato that some historians have seen it as the source and secret of the European population "explosion" of the nineteenth century.[1] But not only in Europe. Grown on poor, hilly soils, the potato, along with peanuts, sweet potatoes, and yams, provided a valuable dietary supplement for a Chinese population that in the eighteenth century began to outstrip the nourishment provided by rice.

In return, Europe brought to the New World new plants—sugar, cereals; and new fauna—the horse, horned cattle, sheep, and new breeds of dog. Some of these served as weapons of conquest; or like the cattle and sheep, took over much of the land from its inhabitants. Worse yet by far, the Europeans and the black slaves they brought with them from Africa carried nasty, microscopic baggage: the viruses of smallpox, measles, and yellow fever; the protozoan parasite of malaria; the bacillus of diphtheria; the rickettsia of typhus; the spirochete of yaws; the bacterium of tuberculosis. To these pathogens, the residents of the Old World had grown diversely resistant. Centuries of exposure within Eurasia had selected human strains that stood up to such maladies. The Amerindians, on the other hand, died in huge numbers, in some places all of them, to the point where only the sparsity of survivors and some happy strains of resistance enabled a few to pull through.

Why the Eurasian biosphere was so much more virulent than the

American is hard to say. Greater population densities and frequency of contagion? The chance distribution of pathogens? Where were the Amerindian diseases? Only one has come down to us—syphilis, which the French called the Italian disease, the Germans the French disease, and so on as it made its way from seaports to the rest of Europe.*

Yet the invaders had their own weaknesses. American visitors to Mexico call travelers' diarrhea "Montezuma's revenge"; those to India speak of "Delhi belly." Such tags are supposed to be funny, but in fact, Europeans migrating to these strange lands in the early centuries fell easy victim to local pathogens and infections and died "like flies."[2] Depending on place. Climate and hygiene—modes of evacuation and waste disposal, water supply and run-off, personal habits, social customs—could make all the difference. Thus the Indian Ocean area was three to four times more virulent than the temperate zones; the West Indies and American tropics up to ten times more; and West Africa was a one-way door to death. Mortality rates there ran fifty times higher.[3] Within these larger regions, higher densities made for festering pestholes: Bombay in India, Batavia in Indonesia. A jacket illustration of Fernand Braudel's trilogy (*Civilisation matérielle,* etc.) shows a well-to-do Portuguese family in Goa dining in a water-covered room: the table stands in water; their feet rest in water. This no doubt kept crawlers from joining the repast, but it was an invitation to enemy swimmers. Forget about flyers.

Oceanic migrations, then, voluntary and involuntary (slaves), brought much death into the world and much woe. But also riches and opportunity for the Europeans, whether leavers or stayers. That is the law of migration in market societies: people go to improve their situation, and so doing, enhance the bargaining power of those left behind; while in their new home they create or seize wealth (food, timber, minerals, or manufactures) to ship or take back to the old country.

These gains were realized only slowly. Not until the nineteenth century did improvements in transport open the American Midwest to commercial agriculture. These same advances made immigration much cheaper and easier, just in time to tap an unprecedented upswing in European population. But even the smaller movements of the earlier period made possible a substantial North American contribution to the food supply of the colonial plantations and the mother countries; and all the rest was there in prospect. European economic and demographic growth in the eighteenth and nineteenth centuries had its strains and pains; but no continent ever modernized more easily. Much of that was due to the New World—was done on the backs of Amerindians, African slaves, indentured servants.

* Some medical ethnologists question the American origin of syphilis, pointing to evidence of pre-Columbian veneral disease in Europe of somewhat similar course and effects. But similar is not identical, and there is no question that syphilis became an epidemic phenomenon only in the sixteenth century. Compare AIDS, which may be older than we know but surfaced as an epidemic disease only in the 1980s.

> If Spain has neither money nor gold nor silver, it is because it has these things, and if it is poor, it is because it is rich. . . . One would think that one wanted to make of this republic a republic of enchanted people living outside the natural order.
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> —Martin Gonzales de Cellorigo, 1600[4]

Well before the agriculture and manufactures came the loot and booty. The Columbian exchange redistributed wealth as well as flora and fauna—a one-stage transfer from old rich to new. The primary economic significance of the influx of wealth from overseas, however, lay in its uneven effects. Some people got rich only to spend; others to save and invest. The same with countries: some were little richer in the end than at the beginning, while others used their new fortune to grow more money.

Ironically, the nations that had started it all, Spain and Portugal, ended up losers. Here lies one of the great themes of economic history and theory. All models of growth, after all, stress the necessity and power of capital—capital as substitute for labor, easer of credit, balm of hurt projects, redeemer of mistakes, great enterprise's second chance, chief nourisher of economic development. Given capital, the rest should follow. And thanks to empire, Spain and Portugal had the capital.

Spain particularly. Its new wealth came in raw, as money to invest or spend. Spain chose to spend—on luxury and war. War is the most wasteful of uses: it destroys rather than builds; it knows no reason or constraints; and the inevitable unevenness and shortage of resources lead to ruthless irrationality, which simply increases costs. Spain spent all the more freely because its wealth was unexpected and unearned. *It is always easier to throw away windfall wealth.*

Who got the money? Short of hoarding, money will be used somehow, go round and come round, for better or worse. Spain wasted much of its wealth on the fields of Italy and Flanders. It went to pay for soldiers and arms, including iron cannon from the English intermittent enemy; for provisions, many of them bought from the Dutch and Flemish intermittent enemy; and for horses and ships.

In the meantime, the wealth of the Indies went less and less to Spanish industry because the Spanish did not have to make things any more; they could buy them.[5] In 1545, Spanish manufacturers had a six-year backlog of orders from the New World. At that time, in principle, the overseas empire was required to buy from Spanish producers only. But customers and profits were waiting, and Spanish merchants turned to foreign suppliers while using their own names to cover the transactions. So much for rules. Nor did the American treasure go to Spanish agriculture; Spain could buy food. As one happy Spaniard put it in 1675, the whole world is working for us:

> Let London manufacture those fabrics of hers to her heart's content; Holland her chambrays; Florence her cloth; the Indies their beaver and vicuna; Milan her brocades; Italy and Flanders their linens, so long as our capital can enjoy them. The only thing it proves is that all nations train journeymen for Madrid and that Madrid is the queen of Parliaments, for all the world serves her and she serves nobody.[6]

Such foolishness is still heard today, in the guise of comparative advantage and neoclassical trade theory. I have heard serious scholars say that the United States need not worry about its huge trade deficit with Japan. After all, the Japanese are giving us useful things in exchange for paper printed with the portrait of George Washington. That sounds good, but it's bad. Wealth is not so good as work, nor riches so good as earnings. A Moroccan ambassador to Madrid in 1690–91 saw the problem clearly:

> . . . the Spanish nation today possesses the greatest wealth and the largest income of all the Christians. But the love of luxury and the comforts of civilization have overcome them, and you will rarely find one of this nation who engages in trade or travels abroad for commerce as do the other Christian nations such as the Dutch, the English, the French, the Genoese and their like. Similarly, the handicrafts practiced by the lower classes and common people are despised by this nation, which regards itself as superior to the other Christian nations. Most of those who practice these crafts in Spain are Frenchmen [who] flock to Spain to look for work . . . [and] in a short time make great fortunes.[7]

Reliance on metics (outsiders) testifies to the inability to mobilize skills or enterprise.

Spain, in other words, became (or stayed) poor because it had too much money. The nations that did the work learned and kept good habits, while seeking new ways to do the job faster and better. The Spanish, on the other hand, indulged their penchant for status, leisure, and enjoyment—what Carlo Cipolla calls "the prevalent *hidalgo* mentality." They were not alone. Everywhere in Europe, genteel living was honored and manual labor scorned; in Spain, however, more so, partly because a frontier, combative society is a poor school for patience and hard work, partly because the crafts and tasks of industry and agriculture were long especially associated with despised minorities such as Jews and Muslims. As the chronicler Bernaldez put it, writing of the Jews at the end of the fifteenth century:

> . . . all of them were merchants, dealers, tax farmers; they were stewards of the nobility and skilled shearers *(oficiales tondadores)*, they were tailors, shoemakers, tanners, beltmakers, weavers, grocers, peddlers, silkmakers, smiths, goldsmiths, and other like professions. None of them cultivated the land; none was a farm worker, carpenter, or mason. All of them looked for easy trades and for ways to make a living with little work.

What is accursed is left to pariahs; and what the pariahs do is accursed.[8] Better to be poor and unemployed. The poor in Spain played a most important role: they helped the rich buy salvation.[9]

By the time the great bullion inflow had ended in the mid-seventeenth century, the Spanish crown was deep in debt, with bankruptcies in 1557, 1575, and 1597. The country entered upon a long decline. Reading this story, one might draw a moral: Easy money is bad for you. It represents short-run gain that will be paid for in immediate distortions and later regrets.*

The nations of northern Europe would have agreed. They throve on the opening of the world. They caught fish, tapped and refined whale oil, grew and bought and resold cereals, wove cloth, cast and forged iron, cut timber and mined coal.[10] They won their own empires, fortunately not endowed with gold and silver. Looting and pillaging when the opportunity offered, they nonetheless built largely on renewable harvests and continuing industry (including the industry of slaves, but

* Ironically, the economists of today have adopted the term "Dutch disease" to describe this syndrome, from the response of the economy of Holland to the discovery and exploitation of natural gas under the North Sea. As though the Dutch did not know how to make the most of these new resources.

that was a negative) rather than on depletable minerals. They built on work.

Europe's shift in economic gravity northward obviously transcends the inglorious Spanish fiasco. The great old mercantile and industrial city-states of Italy—Venice, Florence, Genoa—also lost out. Italy had been at the forefront of the medieval commercial revolution and had led the way out of autarky into international trade and division of labor. As late as the sixteenth century, Italy was a major player, splendid in its manufactures, preeminent in the commercial and banking services rendered to Spain and northern Europe. Yet Italy never really seized the opportunities offered by the Great Opening: one does not find Italian ships in the Indian ocean or crossing the Atlantic. Italy was centered in, caught in, the great Inland Sea. Caught also by old structures: guild controls fettered industry, made it hard to adapt to changing tastes. Labor costs stayed high because manufacture was largely confined to urban, corporate workshops employing adult male craftsmen who had done their years of apprenticeship.[11]

The advance of North over South attracted notice. In the eighteenth century already, observers commented on the difference in psychological terms. Northerners were said to be dour, dull, and diligent. They worked hard and well but had no time to enjoy life. In contrast, the southerners were seen as easygoing and happy, passionate to the point of needing close watching, and given to leisure rather than labor. This contrast was linked to geography and climate: cloudy vs. sunny skies, cold vs. warmth. Some people even found analogous differences within countries: between Lombards and Neapolitans, Catalans and Castilians, Flemings and the *gens du midi,* Scots and Kentishmen.

These stereotypes held an ounce of truth and a pound of lazy thinking. It is easy to dismiss them. But that still leaves the question, why do some fall from high estate and others rise? The "decline and fall" of Spain is like that of Rome: it poses the fascinating problem of success vs. failure, and scholars will never get tired of it.

Probably the most provocative explanation is the one offered by the German social scientist Max Weber. Weber, who began as a historian of the ancient world but grew into a wonder of diversified social science, published in 1904–05 one of the most influential and provocative essays ever written: "The Protestant Ethic and the Spirit of Capitalism." His thesis: that Protestantism—more specifically, its Calvinist branches—promoted the rise of modern capitalism, that is, the industrial capitalism that he knew from his native Germany. Protestantism did this, he said, not by easing or abolishing those aspects of the Roman faith that had deterred or hindered free economic activity (the prohibition of usury, for example); nor by encouraging, let alone inventing, the pursuit of wealth; but by defining and sanctioning an ethic of everyday behavior that conduced to business success.

Calvinistic Protestantism, said Weber, did this initially by affirming the doctrine of predestination. This held that one could not gain salvation by faith or deeds; that question had been decided for everyone from the beginning of time, and nothing could alter one's fate.

Such a belief could easily have encouraged a fatalistic attitude. If behavior and faith make no difference, why not live it up? Why be good? Because, according to Calvinism, goodness was a plausible sign of election. Anyone could be chosen, but it was only reasonable to suppose that most of those chosen would show by their character and ways the quality of their souls and the nature of their destiny. This implicit reassurance was a powerful incentive to proper thoughts and behavior. As the Englishwoman Elizabeth Walker wrote her grandson in 1689, alluding to one of the less important but more important signs of grace, "All cleanly people are not good, but there are few good people but are cleanly."[12] And while hard belief in predestination did not last more than a generation or two (it is not the kind of dogma that has lasting appeal), it was eventually converted into a secular code of behavior: hard work, honesty, seriousness, the thrifty use of money and time (both lent us by God).* "*Time* is *short,*" admonished the Puritan divine Richard Baxter (1615–1691), "and *work* is *long.*"[13]

All of these values help business and capital accumulation, but Weber stressed that the good Calvinist did not aim at riches. (He might easily believe, however, that honest riches are a sign of divine favor.) Europe did not have to wait for the Protestant Reformation to find people who wanted to be rich. Weber's point is that Protestantism produced a new kind of businessman, a different kind of person, one who aimed to live and work a certain way. It was the *way* that mattered, and riches were at best a by-product.

A good Calvinist would say, that was what was wrong with Spain: easy riches, unearned wealth. Compare the Protestant and Catholic

* The best analysis of the Weberian model is still Talcott Parsons's *Structure of Social Action.* Elaborating the paradigm, Parsons divides action into three categories: rational (appropriate to ends), irrational (unrelated to ends), and nonrational (action as an end in itself). A good example of this last: "Father, I cannot tell a lie; it was I cut down the cherry tree." Weber's Calvinist ethic falls in the realm of the nonrational.

attitudes toward gambling in the early modern period. Both condemned it, but Catholics condemned it because one might (would) lose, and no responsible person would jeopardize his well-being and that of others in that manner. The Protestants, on the other hand, condemned it because one might win, and that would be bad for character. It was only much later that the Protestant ethic degenerated into a set of maxims for material success and smug, smarmy sermons on the virtues of wealth.

The Weber thesis gave rise to all manner of rebuttal. Roman Catholics did not know whether to accept it as praise or denounce it as criticism. Materialist historians rejected the notion that abstractions such as values and attitudes, let alone those inspired by religion, could motivate and shape the mode of production. This refusal was the stronger for Max Weber's explicit and sacrilegious intention to rebut Marx on this score. To get cart and horse in proper order, some argued that the rise of capitalism had generated Protestantism; or that Protestantism appealed to the kinds of people—tradesmen, craftsmen—whose personal values already led to hard work and business success.[14]

In an influential study called *Religion and the Rise of Capitalism,* the English social historian R. H. ("Harry") Tawney rejected the link between Protestantism and economic growth. The English economy, he said, took off in the sixteenth century only when religious influence diminished, to be replaced by secular attitudes. One thing he did grant to the Puritan-Dissenter ethic: it shielded tradesmen and manufacturers against the slings and arrows of genteel contempt. It gave them a sense of dignity and righteousness, armor in a world of anticommercial prejudices. And so, not yielding to the temptation of a higher leisure, good Calvinists kept at their task from generation to generation, accumulating wealth and experience along the way.[15]

The same kind of controversy has swirled around the derivative thesis of the sociologist Robert K. Merton, who argued that there was a direct link between Protestantism and the rise of modern science. He was not the first to make this point. In the nineteenth century Alphonse de Candolle, from a Huguenot family of Geneva, counted that of ninety-two foreign members elected to the French Académie des Sciences in the period 1666–1866, some seventy-one were Protestant, sixteen Catholic, and the remaining five Jewish or of indeterminate religious affiliation—this from a population pool outside of France of 107 million Catholics, 68 million Protestants. A similar count of foreign fellows of the Royal Society in London in 1829 and 1869 showed equal numbers of Catholics and Protestants out of a pool in which

Catholics outnumbered Protestants by more than three to one.[16]

Much of this no doubt reflected the greater access of Catholics in Catholic countries to the older liberal professions and the governing bureaucracy, and hence their preference for a different kind of schooling. But much was dictated by the fears of the clerical hierarchy, by their distaste for the findings and paradigms of a science that negated religious doctrine. As the English chemist and Unitarian minister Joseph Priestley put it, the pope, in patronizing science, "was cherishing an enemy in disguise," for he had "reason to tremble even at an air pump, or an electrical machine."[17]

Against all of this, one scholar has categorically asserted that there is no empirical basis for the alleged link;[18] that Weber's data on differential education of Catholics and Protestants in the Germany of the turn of the century (Protestants more inclined to commercial and scientific programs) are badly calculated; that Catholic and non-Calvinist businessmen did as well as Weber's ideal Calvinist types; that one might as well explain the differences between northern and southern Europe by geography or race; and that Max Weber is like the tailors who clothed the Chinese emperor, and his Protestant connection much ado about nothing.

Indeed, it is fair to say that most historians today would look upon the Weber thesis as implausible and unacceptable: it had its moment and it is gone.

I do not agree. Not on the empirical level, where records show that Protestant merchants and manufacturers played a leading role in trade, banking, and industry.[19] In manufacturing centers *(fabriques)* in France and western Germany, Protestants were typically the employers, Catholics the employed. In Switzerland, the Protestant cantons were the centers of export manufacturing industry (watches, machinery, textiles); the Catholic ones were primarily agricultural. In England, which by the end of the sixteenth century was overwhelmingly Protestant, the Dissenters (read Calvinists) were disproportionately active and influential in the factories and forges of the nascent Industrial Revolution.

Nor on the theoretical. The heart of the matter lay indeed in the making of a new kind of man—rational, ordered, diligent, productive. These virtues, while not new, were hardly commonplace. Protestantism generalized them among its adherents, who judged one another by conformity to these standards. This is a story in itself, one that Weber did surprisingly little with: the role of group pressure and mutual scrutiny in assuring performance—everybody looking at everyone else and minding one another's business.

Two special characteristics of the Protestants reflect and confirm this link. The first was stress on instruction and literacy, for girls as well as boys. This was a by-product of Bible reading. Good Protestants were expected to read the holy scriptures for themselves. (By way of contrast, Catholics were catechized but did not have to read, and they were explicitly discouraged from reading the Bible.) The result: greater literacy and a larger pool of candidates for advanced schooling; also greater assurance of continuity of literacy from generation to generation. *Literate mothers matter.*

The second was the importance accorded to time. Here we have what the sociologist would call unobtrusive evidence: the making and buying of clocks and watches. Even in Catholic areas such as France and Bavaria, most clockmakers were Protestant; and the use of these instruments of time measurement and their diffusion to rural areas was far more advanced in Britain and Holland than in Catholic countries.[20] Nothing testifies so much as time sensibility to the "urbanization" of rural society, with all that that implies for rapid diffusion of values and tastes.

This is not to say that Weber's "ideal type" of capitalist could be found only among Calvinists and their later sectarian avatars. People of all faiths and no faith can grow up to be rational, diligent, orderly, productive, clean, and humorless. Nor do they have to be businessmen. One can show and profit by these qualities in all walks of life. Weber's argument, as I see it, is that in that place and time (northern Europe, sixteenth to eighteenth centuries), religion encouraged the appearance in numbers of a personality type that had been exceptional and adventitious before; and that this type created a new economy (a new mode of production) that we know as (industrial) capitalism.

Add to this the growing need for fixed capital (equipment and plant) in the industrial sector. This made continuity crucial—for the sake of continued maintenance and improvement and the accumulation of knowledge and experience. These manufacturing enterprises were very different in this regard from mercantile ones, which often took the form of ad hoc mobilizations of capital and labor, brought together for a voyage or venture and subsequently dissolved. (Recall that the English East India Company operated in this way in the early years, although there too it was soon apparent that a continuing mobilization would be necessary.)

For these requirements of a new kind of economy, the Weberian entrepreneur was specially suited by temperament and habit; and here the Tawney emphasis on the link between self-respect and continuity is especially pertinent. It is no coincidence that the French crown, always ready and willing to honor socially ambitious bourgeois (typically men of law) with patents of nobility—for a price, of course—began in the seventeenth century to permit noblemen to engage in wholesale (as opposed to retail) trade; and in the eighteenth century to impose on aspirants from industry a condition of continuity. The newly ennobled *négociant* or *fabricant* was required to remain "in trade"—a condition that would once have been perceived as inherently *déshonorante,* incompatible with such exalted status.[21] The problem, as a good Calvinist would have seen it, was that honors and pretensions ill became men of the countinghouse and *fabrique.* They worked better and harder dressed in dark woolen cloth, without silk, lace, and wig.

However important this proliferation of a new business breed, it was only one aspect of shifting economic power and wealth from South to North. Not only money moved, but knowledge as well; and it was knowledge, specifically scientific knowledge, that dictated economic possibilities. In the centuries before the Reformation, southern Europe was a center of learning and intellectual inquiry: Spain and Portugal, because they were on the frontier of Christian and Islamic civilization and had the benefit of Jewish intermediaries; and Italy, which had its own contacts. Spain and Portugal lost out early, because religious passion and military crusade drove away the outsiders (Jews and then the *conversos*) and discouraged the pursuit of the strange and potentially heretical; but Italy continued to produce some of Europe's leading mathematicians and scientists. It was not an accident that the first learned society (the Accadémia dei Lincei, Rome, 1603) was founded there.*

The Protestant Reformation, however, changed the rules. It gave a big boost to literacy, spawned dissents and heresies, and promoted the skepticism and refusal of authority that is at the heart of the scientific endeavor. The Catholic countries, instead of meeting the challenge, responded by closure and censure. The reaction in the Habsburg dominions, which included the Low Countries, followed hard on the heels of Luther's denunciation. The presence there of Marrano refugees, feared and hated as enemies of the true Church and accused of deliberately propagating the new doctrines, aggravated the hysteria.

A rain of interdictions followed (from 1521 on), not only of publishing but of reading heresy, in any language. The Spanish authorities,

* Lincei = lynxes. The animal was chosen for its reputedly keen sight.

both lay and clerical, viewed Lutherans (all Protestants were then seen as Lutherans), not as dissenters, but as non-Christians, like Jews and Muslims enemies of the faith.[22] Any thoughts of ending the Inquisition were shelved, and Church and civil authorities joined to control thought, knowledge, and belief. In 1558, the death penalty was introduced for importing foreign books without permission and for unlicensed printing. Universities reduced to centers of indoctrination; unorthodox and dangerous books were placed on an *Index Librorum Prohibitorum* (1557 in Rome, 1559 in Spain), and safe books appeared with an official *imprimatur* ("let it be printed"). Among the books on the Spanish list: scientific works banned because their authors were Protestant. Despite smuggling, hazardous to the health, the diffusion of new ideas to society at large slowed to a trickle. (Recall the book review and purge at the beginning of *Don Quixote*. The point is not only the role of whim, but the absurd reasons—the trivia that brought risk in a fantasy-ridden, knowledge-starved society.)

Nor were Spaniards allowed to study abroad, lest they ingest subversive doctrine. That same year (1559), the crown forbade attendance at foreign universities except for such safe centers as Rome, Bologna, and Naples. The effect was drastic. Spanish students had long gone to the University of Montpellier for medical training; they just about stopped going—248 students from 1510 to 1559; 12 from 1560 to 1599.[23] (One wonders about those dozen mavericks.) Subversive scientists were silenced and forced to denounce themselves. Regimes that exercise thought control and enforce orthodoxy are never satisfied with prohibitions and punishments. The guilty must confess and repent—both for their own and for others' salvation.

Persecution led to an interminable "witch hunt," complete with paid snitches, prying neighbors, and a racist blood mania *(limpieza de sangre)*. Judaizing conversos were caught by telltale vestiges of Mosaic practice: refusal of pork, fresh linen on Friday, an overheard prayer, irregular church attendance, a misplaced word. Cleanliness especially was cause for suspicion, and bathing was seen as evidence of apostasy, for Marranos and Moriscos alike. "The phrase 'the accused was known to take baths . . . ' is a common one in the records of the Inquisition."[24] Inherited dirt: clean people don't have to wash. In all this, the Spanish and Portuguese demeaned and diminished themselves. Intolerance can harm the persecutor more than the victim.

So Iberia and indeed Mediterranean Europe as a whole missed the train of the so-called scientific revolution. In the 1680s Juan de Cabriada, a Valencian physician, was conducting a running war with doctors

in Madrid, trying vainly to persuade them to accept Harvey's discovery of the circulation of the blood in the face of antique Galenist tradition. What, he asked, was wrong with Spain? It is "as if we were Indians, always the last" to learn of new knowledge.[25]

The British historian Hugh Trevor-Roper has argued that this reactionary, anti-Protestant backlash, more than Protestantism itself, sealed the fate of southern Europe for the next three hundred years.[26] Such retreat was neither predestined nor required by doctrine. But this path once taken, the Church, repository and guardian of truth, found it hard to admit error and change course. How hard? One hears nowadays that Rome has finally, almost, rehabilitated Galileo after almost four hundred years. That's how hard.

The Condemnation of Galileo

Galileo Galilei was not a saint, but he was a genius and a treasure—for Florence, Italy, Europe, and the world. He was a pioneer of experimental science, a keen observer (as befit a member of the Academy of Lynxes), a sharp thinker, and a powerful polemicist and debater. Yet in 1633 he was condemned by the Roman Church for contumacy and heresy: "The opinion that the Sun is at the center of the world and immobile is absurd, false in philosophy, and formally heretical, because it is expressly contrary to Holy Scripture."

(Galileo was not the first; or the last. Equally momentous, if less remembered, was the burning in Rome in February 1600 of Giordano Bruno, ex-Dominican, a philosopher whose imaginary concept of the universe came far closer to what we now think than that of Copernicus or Galileo: infinite space, billions of burning stars, rotating earth revolving around the sun, matter composed of atoms, and so on. All heresies, linked to mysteries and magic. In effect, by burning Bruno, the Church proclaimed its intention of taking science and imagination in hand and leashing them to Rome.[27] But while Galileo worked and spoke, freedom still had room.)

That was the sentence. The confession of error by Galileo was some fourteen times as long. The point was not to pronounce dogma, but to denounce heresy and to display for all, in great detail, the admission of the sinner, his recognition and acceptance of the authority of the Holy Church, and his sincere promise of repentance.

Never again. That is the nature of thought control in infallible systems: these aim not so much to convict as to convince—both the guilty one and all other members of the system.

Why the Church chose to make an issue of geocentrism remains a puzzle. Nothing in holy scripture seems to require such belief. To be sure, the Bible does use images of the sun crossing the sky or stopping in its course, but it is not hard to treat those as expressions, sometimes metaphorical, of what the eye on earth perceives. The Roman Curia could have ignored the matter without rending the tissue of faith and obedience. Yet any church is tempted to rest its authority on doctrine and dogma, for these are the sign and instrument of rule, especially in troublous times.

Meanwhile Galileo, for reasons as much of temperament as of intellectual integrity, enjoyed doing battle. A redoubtable debater, he would not suffer fools and found them aplenty in clerical circles. This was a dangerous game in a Roman world of virtually unlimited authority, intrigue and ambition, slander and treachery. Byzantium on the Tiber: nothing in Rome made contenders happier than the early demise of the Holy Father, for every change of pope entailed a reshuffling of power and place. Here today, gone tomorrow; friend now, foe later. Galileo could count on no one.

Even worse, perhaps, Galileo's response to hints and warnings of disapproval was to "go public"—to publish in Italian rather than in Latin—and thereby go over the head of the insiders and appeal to a larger audience. In effect he was popularizing (vulgarizing) heresy, and that was intolerable.*

So Galileo confessed; and although he is said to have made one last, stubborn demurrer (*"Eppure si muove"* [Say what you will, it moves]), he went into a stultifying house arrest that ended his career as an effective, innovating scientist. And that was a catastrophic loss to Italian science, which, so long as the great man worked and thrived, had stood up to the growing constraint implicit in the Counter-Reformation.

And what about science in other lands? In the Protestant countries, the condemnation meant little. If anything, it confirmed these rebels against Church authority in their scorn for the superstitions of Rome. Father Gassendi, professor at Aix-en-Provence and excellent observer of astronomical phenomena, went to Holland in 1632 and wrote back to a French colleague about attitudes toward the Copernican paradigm: "All those people there are for it."[28] That may have been an exaggeration, but it captures the contrast with what he had known at home. Holland, England, and the Protestant countries in general were a different state of mind.

In France, the savants swung between sense and sensibility, integrity and obedience. The same Gassendi, writing to Galileo, pleaded with him to make peace with Rome and his conscience—and both at the same time: "I am in the greatest anxiety about the fate that awaits you, O you, the great glory of the century! If the Holy See has decided something against your opinion, bear with it as suits a wise man. Let it suffice you to live with the conviction that you have sought only the truth."[29]

Only the truth. But what was truth? Within the knowledge available at that time, Copernicus alone left much to be desired. The Copernican-Keplerian paradigm fitted the observations better, but did that prove that the earth went around the sun? Better and safer to stick to experiment and not ask why. Here lay a way of continuing observation while denying consequences, and this evasion found a welcome with some of the leading French scientists of the day.* Thus Mersenne, prime communicator among European savants, wrote in 1634 that everything anyone had said about the movement of the earth did not prove the point; and he dropped plans to do a book on heliocentrism. Gassendi, the same. Descartes, the same. The great Descartes came up with his own twist: the heavenly bodies were not governed in their movements by some kind of pull, an invisible, magical attraction, but by whirling pools of force that bore them along. Attraction smacked of superstition, whereas whirlpools were somehow scientific. In the event, said Descartes, the earth was carried in its field of force like a passenger on a boat. The boat moved, but the passenger did not. So the earth did not move. *Q.E.D.*

* Compare the long-standing Italian rule about publication of pornography: so long as the book was costly and appeared in a limited edition, it was tolerable; but no cheap editions could be allowed, for fear of corrupting those simple folk who did not have the cultural resources to resist temptation and sin. On the Church's fear of the vernacular, cf. the troubles of Giambattista della Porta in the 1580s. Eamon, "From the Secrets of Nature," p. 361, n. 41.

* As it did in Italy. Compare the short-lived Accadémia del Cimento, organized and patronized by Duke Leopold of Tuscany, summoned at his beck and call and dissolved after his departure for Rome to pursue higher callings. No intellectual autonomy: the members reported on their experiments, but that was all—science, in other words, without *scientia*.

Even with such cleverness, Descartes found it hard to live in a France of Jesuitical subtleties. He moved to Holland and left no forwarding address, except with Mersenne. Meanwhile the French slowly, reluctantly, came around to his cosmology, and once there, clung to the Cartesian system by way of refusing Newtonian theories of motion and gravity. Better push than pull. For Newton was English, and the French, then as now, found it hard to learn from others *(nous n'avons pas de leçons à recevoir . . .)*, especially from their traditional enemy of Agincourt and Crécy. An outrageous instance of this intellectual chauvinism came in the 1980s, when French health authorities insisted on distributing contaminated blood rather than purchase American tests and decontaminating equipment. (The United States has replaced Britain as the Gallic *bête noire,* the worse for having helped in two world wars.) French authorities thereby condemned hundreds, maybe thousands, to AIDS and death.

When the French finally did reconcile themselves to Newtonian mathematics and physics, they did very well. They had talent and genius in abundance. But they lost several generations to pride.

The Tenacity of Intolerance and Prejudice[30]

Fifteenth-century Sicily had the misfortune to owe allegiance to the crown of Castile; so when Ferdinand and Isabella in 1492 ordered the expulsion or conversion of the Jews of Spain, Sicily had to go along. Not that the island lacked anti-Jewish sentiment, as a number of earlier pogroms showed. But Jews had lived there for centuries and played a disproportionate role in Sicily's trade, to say nothing of their place as doctors and apothecaries. The Sicilian viceroy dithered, reluctant to issue the fateful decree; but a series of orders prepared the way by prohibiting Jews from selling their assets, compelling them to pay all debts outstanding, and—most ominous—barring them from bearing arms.

One need not go into detail. The Jews of the island won a short delay; they were also granted benevolent permission to take with them the clothes on their back, a mattress, a wool or serge blanket, a pair of sheets, and some small change, plus some food for the way.

We are told that many Sicilians were sorry to see them go. With reason. What was left of trade shrank almost to nothing; houses and even neighborhoods were left desolate; and we must assume that some people had the decency to feel ashamed.

Much later, toward the end of the seventeenth century, some Sicilians urged the king to do something to promote trade. Charles II granted Messina the privilege of a free port and gave Jews the right to trade there—on condition that they sleep outside the city and wear a distinctive sign on their clothing. Such ambiguous hospitality did not encourage Jews to come, so in 1728 the Jews were granted the right to trade anywhere on the island, to reside in Messina, to have a synagogue and cemetery, to own and dispose of property. Even this did not help, so in 1740 the king explicitly invited the Jews to return. A number of families accepted, but found themselves mistreated by a prejudiced populace. Then it happened that the queen had not succeeded in bearing a male heir to the throne, and the royal couple were persuaded by clerics that they would not have a son so long as they allowed the Jews to stay. So, after seven years, another expulsion.

Intolerance, superstition, ignorance—these are easier to acquire and cultivate than to uproot. The same iniquities and vices, perpetrated long ago by foreign (Spanish) rulers, have contributed to this day to Sicily's persistent backwardness.

13

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,

* 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*.

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.

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

* 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

* 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.

and before refiners had techniques to deal with coke-smelted pig (Henry Cort, patents of 1783 and 1784). 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;

* 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.

* 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

* 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.

* 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

* 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, 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

* 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.

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.

14

Why Europe? Why Then?

> If we were to prophesy that in the year 1930 a population of fifty million, better fed, clad, and lodged than the English of our time, will cover these islands, that Sussex and Huntingdonshire will be wealthier than the wealthiest parts of the West Riding of Yorkshire now are . . . that machines constructed on principles yet undiscovered will be in every house . . . many people would think us insane.
>
> —MACAULAY, "Southey's Colloquies on Society" (1830)[1]

Why Industrial Revolution there and then? The question is really twofold. First, why and how did any country break through the crust of habit and conventional knowledge to this new mode of production? After all, history shows other examples of mechanization and use of inanimate power without producing an industrial revolution. One thinks of Sung China (hemp spinning, ironmaking), medieval Europe (water- and windmill technologies), of early modern Italy (silk throwing, shipbuilding), of the Holland of the "Golden Age." Why now, finally, in the eighteenth century?

Second, why did Britain do it and not some other nation?

The two questions are one. The answer to each needs the other. That is the way of history.

Turning to the first, I would stress *buildup*—the accumulation of knowledge and knowhow; and *breakthrough*—reaching and passing thresholds. We have already noted the interruption of Islamic and Chinese intellectual and technological advance, not only the cessation of improvement but the institutionalization of the stoppage. In Europe, just the other way: we have continuing accumulation. To be sure, in Europe as elsewhere, science and technology had their ups and downs,

areas of strength and weakness, centers shifting with the accidents of politics and personal genius. But if I had to single out the critical, distinctively European sources of success, I would emphasize three considerations:

(1) the growing *autonomy* of intellectual inquiry;

(2) the development of unity in disunity in the form of a common, implicitly adversarial *method*, that is, the creation of a language of proof recognized, used, and understood across national and cultural boundaries; and

(3) the invention of invention, that is, the *routinization* of research and its diffusion.

Autonomy: The fight for intellectual autonomy went back to medieval conflicts over the validity and authority of tradition. Europe's dominant view was that of the Roman Church—a conception of nature defined by holy scripture, as reconciled with, rather than modified by, the wisdom of the ancients. Much of this found definition in Scholasticism, a system of philosophy (including natural philosophy) that fostered a sense of omnicompetence and authority.

Into this closed world, new ideas necessarily came as an insolence and a potential subversion—as they did in Islam. In Europe, however, acceptance was eased by practical usefulness and protected by rulers who sought to gain by novelty an advantage over rivals. It was not an accident, then, that Europe came to cultivate a vogue for the new and a sense of progress—a belief that, contrary to the nostalgia of antiquity for an earlier grace (Paradise Lost), the Golden Age (utopia) actually lay ahead; and that people were now better off, smarter, more capable than before. As Fra Giordano put it in a sermon in Pisa in 1306 (we should all be remembered as long): "But not all [the arts] have been found; we shall never see an end of finding them . . . and new ones are being found all the time."[2]

Of course, older attitudes hung on. (A law of historical motion holds that all innovations of thought and practice elicit an opposite if not always equal reaction.) In Europe, however, the reach of the Church was limited by the competing pretensions of secular authorities (Caesar vs. God) and by smoldering, gathering fires of religious dissent from below. These heresies may not have been enlightened in matters intellectual and scientific, but they undermined the uniqueness of dogma and, so doing, implicitly promoted novelty.

Most shattering of authority was the widening of personal experience. The ancients, for example, thought no one could live in the tropics: too hot. Portuguese navigators soon showed the error of such preconceptions. Forget the ancients, they boasted; "we found the contrary." Garcia d'Orta, son of *converso* parents and himself a loyal but of course secret Jew, learned medicine and natural philosophy in Salamanca and Lisbon, then sailed to Goa in 1534, where he served as physician to the Portuguese viceroys. In Europe, intimidated by his teachers, he never dared to question the authority of the ancient Greeks and Romans. Now, in the nonacademic environment of Portuguese India, he felt free to open his eyes. "For me," he wrote, the testimony of an eye-witness is worth more than that of all the physicians and all the fathers of medicine who wrote on false information"; and further, "you can get more knowledge now from the Portuguese in one day than was known to the Romans after a hundred years."[3]

Method: Seeing alone was not enough. One must understand and give nonmagical explanations for natural phenomena. No credence could be given to things unseen. No room here for unicorns, basilisks, and salamanders. Where Aristotle thought to explain phenomena by the "essential" nature of things (heavenly bodies travel in circles; terrestrial bodies move up or down), the new philosophy proposed the converse: nature was not in things; things were (and moved) in nature. Early on, moreover, these searchers came to see mathematics as immensely valuable for specifying observations and formulating results. Thus Roger Bacon at Oxford in the thirteenth century: "All categories depend on a knowledge of quantity, concerning which mathematics treats, and therefore the whole power of logic depends on mathematics."[4] This marriage of observation and precise description, in turn, made possible replication and verification. Nothing so effectively undermined authority. It mattered little who said what, but what was said; not perception but reality. Do I see what you say you saw?

Such an approach opened the way to purposeful experiment. Instead of waiting to see something happen, make it happen. This required an intellectual leap, and some have argued that it was the renewal and dissemination of magical beliefs (even Isaac Newton believed in the possibility of alchemy and the transmutation of matter) that led the scientific community to see nature as something to be acted upon as well as observed.[5] "In striking contrast to the natural philosopher," writes one historian, "the magician manipulated nature."[6]

Well, at least he tried. I am skeptical, however, of this effort to conflate personal confusions with larger causation. The leap from observation to experiment, from passive to active, was hard enough, and the temptations of magic, this "world of profit and delight, of power, of

honor, of omnipotence," were diversion and obstacle. If anything, the world of magic was a parody of reality, a shrinking residual of ignorance, a kind of intellectual antimatter. Magic's occasional successes were serendipitous by-products of hocus-pocus. Its practitioners were easily seen as crazies, if not as agents of the devil, in part because of their frequently eccentric manner and occasionally criminal behavior.* Such practices went back to the dawn of time; they are still with us and always will be, because, like people who play the lottery, we want to believe. That they revived and flourished in the rush of new knowledge, of secrets uncovered, of mysteries revealed, should come as no surprise. Magic was more response than source, and insofar as it played a role, it was less as stimulant than as allergenic.[7]

Note that for some, this is cause for regret, as at a self-imposed impoverishment: " . . . the new quantitative and mechanistic approach eventually established a metaphysics which left no room for essences, animism, hope, or purpose in nature, thus making magic something 'unreal,' or supernatural in the modern sense."[8] Not to feel bad: the road to truth and progress passed there. As David Gans, an early seventeenth-century popularizer of natural science, put it, one knows that magic and divining are not science because their practitioners do not argue with one another. Without controversy, no serious pursuit of knowledge and truth.[9]

This powerful *combination* of perception with measurement, verification, and mathematized deduction—this new method—was the key to knowing. Its practical successes were the assurance that it would be protected and encouraged whatever the consequences. Nothing like it developed anywhere else.[10]

How to experiment was another matter. One first had to invent research strategies and instruments of observation and measurement, and almost four centuries would elapse before the method bore fruit in the spectacular advances of the seventeenth century. Not that knowledge stood still. The new approach found early application in astronomy and navigation, mechanics and warfare, optics and surveying—all of them practical matters. But it was not until the late sixteenth century, with Galileo Galilei, that experiment became a system. This en-

* Hence the poison scandal (*l'affaire des poisons*) of the 1680s in France, which saw hundreds of fortunetellers, astrologers, and their clients arrested and strenuously interrogated, and some thirty-four executed for complicity in murder. Nothing, says Grenet, *La passion des astres,* pp. 136–59, did more to discredit astrology and magic among the larger public and the political authorities. The scientists had already abandoned this nonsense.

tailed not only repeated and repeatable observation, but deliberate simplification as a window on the complex. Want to find the relations between time, speed, and distance-covered of falling objects? Slow them by rolling them down an inclined plane.

Scientists had to see better and could do so once the telescope and microscope were invented (c. 1600), opening new worlds comparable for wonder and power to the earlier geographical discoveries. They needed to measure more precisely, because the smallest shift of a pointer could make all the difference. So Pedro Nuñez, professor of astronomy and mathematics in the University of Coimbra (Portugal), invented in the early sixteenth century the *nonius* (from his latinized name), to give navigational and astronomical readings to a fraction of a degree. This was later improved by the vernier scale (Pierre Vernier, 1580–1637), and this in turn was followed by the invention of the micrometer (Gascoigne, 1639, but long ignored; and Adrien Auzout, 1666), which used fine wires for reading and a screw (rather than a slide) to achieve close control. The result was measures to the tenth and less of a millimeter that substantially enhanced astronomical accuracy.[11] (Note that just learning to make precision screws was a major achievement; also that the usefulness of these instruments depended partly on eyeglasses and magnifying lenses.)

The same pursuit of precision marked the development of time measurement. Astronomers and physicists needed to time events to the minute and second, and Christian Huygens gave that to them with the invention of the pendulum clock in 1657 and the balance spring in 1675. Scientists also needed to calculate better and faster, and here John Napier's logarithms were as important in their day as the invention of the abacus in an earlier time, or of calculators and computers later.[12] And they needed more powerful tools of mathematical analysis, which they got from René Descartes's analytic geometry and, even more, from the new calculus of Isaac Newton and Gottfried Wilhelm von Leibniz. These new maths contributed immensely to experiment and analysis.

Routinization: The third institutional pillar of Western science was the routinization of discovery, the invention of invention. Here was a widely dispersed population of intellectuals, working in different lands, using different vernaculars—and yet a community. What happened in one place was quickly known everywhere else, partly thanks to a common language of learning, Latin; partly to a precocious development of courier and mail services; most of all because people were moving in all directions. In the seventeenth century, these links were institutionalized, first in the person of such self-appointed human switchboards as Marin Mersenne (1588–1648), then in the form of learned societies with their corresponding secretaries, frequent meetings, and periodical journals. The earliest societies appeared in Italy—the Accadémia dei Lincei (the Academy of Lynxes) in Rome in 1603, the short-lived Accadémia del Cimento in Florence in 1653. More important in the long run, however, were the northern academies: the Royal Society in London in 1660, the Academia Parisiensis in 1635, and the successor Académie des Sciences in 1666. Even before, informal but regular encounters in coffeehouses and salons brought people and questions together. As Mersenne put it in 1634, "the sciences have sworn inviolable friendship to one another."[13]

Cooperation, then, but enormously enhanced by fierce rivalry in the race for prestige and honor. In the pre-academy environment of the sixteenth century, this often took the form of concealment, of partial divulgence, of refusal to publish, of saving the good parts for debate and confutation.[14] Even in the late seventeenth century, one has the eccentric figure of Robert Hooke, active member of the Royal Society, whose motto might have been, "I thought of that first." If we can believe him, he put all manner of valuable creations in his cabinet drawers, only to bring them out when someone else had come up with a comparable device. In this way, he challenged Christian Huygens on the invention of the watch balance spring (1675), a major advance in the accuracy of portable timepieces. History has given the palm to Huygens, not only because his spiral spring was tried in a watch and worked, but also because he announced his invention when he made it. One cannot have these unprovable claims *ex post,* not even from so gifted a mechanical genius as Hooke.[15]

In general, fame was the spur, and even in those early days, science was a contest for priority. That was why it became so important to show-and-tell to aficionados, often in elegant salons; these ladies and gentlemen were witnesses to achievement. And that was why scientists, amateur and professional, were so keen to found journals and get dated articles published. Also to replicate experiments, verify results, correct, improve, go beyond. Here again the role of the printing press and movable type was crucial; also the shift from Latin, an invaluable means of international communication among savants of different countries, to the vernacular, the language of the larger public. Again, nothing like these arrangements and facilities for propagation was to be found outside Europe.

Scientific method and knowledge paid off in applications—most importantly in power technology. During these centuries, the older power devices—the windmill and water wheel—got continuing attention, with some gain in efficiency; but the great invention would be the conversion of heat energy into work by means of steam. No technique drew so closely on experiment—a long inquiry into vacuums and air pressure that began in the sixteenth century and reached fruition in the late seventeenth in the work of Otto von Guericke (1602–1686), Evangelista Torricelli (1608–1647), Robert Boyle (1627–1691), and Denys Papin (?1647–1712), German, Italian, English, French. To be sure, the scientists of the eighteenth century could not have explained why and how a steam engine worked. That had to wait for Sadi Carnot (1796–1832) and the laws of thermodynamics. But to say that the engine anticipated knowledge is not to say that the engine builder did not draw on earlier scientific acquisitions, both substantive and methodological. James Watt made the point. His master and mentor Joseph Black (1728–1799) did not give him the idea for the separate condenser, but working with Black gave him the practice and method to probe and resolve the issue.[16] Even at that, the heroic inventor did not give full credit. Watt was a friend of professors in Edinburgh and Glasgow, of eminent natural philosophers in England, of scientists abroad. He knew his mathematics, did systematic experiments, calculated the thermal efficiency of steam engines; in short, built on accumulated knowledge and ideas to advance technique.[17]

All of this took time, and that is why, *in the long,* the Industrial Revolution had to wait. It could not have happened in Renaissance Florence. Even less in ancient Greece. The technological basis had not yet been laid; the streams of progress had to come together.

The answer *in the short* lies in conjuncture, in the relations of supply and demand, in prices and elasticities. Technology was not enough. What was needed was technological change of mighty leverage, the kind that would resonate through the market and change the distribution of resources.

Let me illustrate. In fourteenth-century Italy, gifted mechanics (we do not know their names) found ways to throw silk, that is, to spin silk warp, by machine; and even more impressive, to drive these devices by waterpower. On the basis of this technique, the Italian silk industry prospered for centuries, to the envy of other countries. The French managed to pierce the secret in 1670, the Dutch at about the same time; and in 1716, Thomas Lombe, after some years of patient espionage, brought the technique to England and built a large water-powered mill employing hundreds of people.[18]

This was a factory, comparable in almost every way to the cotton mills of a later era. Almost . . . the difference was that the Lombe mill at Derby, along with the hand-operated throwsters' shops that had preceded it and some smaller machine imitators, was more than enough to accommodate England's demand for silk yarn. Silk, after all, was a costly raw material, and the silk manufacture catered to a small and affluent clientele. So the Lombe mill, fifty years ahead of those first cotton mills of the 1770s, was not the model for a new mode of production. One could not get an industrial revolution out of silk.[19]

Wool and cotton were something else again. When wool sneezed, all Europe caught cold; cotton, and the whole world fell ill. Wool was much the more important in Europe, and cotton's role in the Industrial Revolution was in some ways an accident. The British "calico acts" (1700 and 1721), which prohibited the import and even wearing of East Indian prints and dyestuffs, were intended to protect the native woolen and linen manufacturers, but inadvertently sheltered the still infant cotton industry; and while cotton was a lusty infant, it was still much smaller than the older branches at midcentury. The first attempts to build spinning machines aimed at wool, because that was where the profit lay. But when wool fibers proved troublesome and cotton docile, inventors turned their attention to the easier material.

Also, the encrustation of the woolen industry and the vested power of its workforce impeded change. Cotton, growing fast, recruiting new hands, found it easier to impose new ways. This is a constant of technological innovation as process: it is much easier to teach novelty to inexperienced workers than to teach old dogs new tricks.*

Why the interest in mechanization? Primarily because the growth of the textile industry was beginning to outstrip labor supply.† England

* On the resistance of workers in wool to mechanization, see especially Randall, *Before the Luddites,* who points out this response was also a function of organization and the sharing of gain. Where the workers were in effect independent agents, as in Yorkshire, they had little trouble adopting new ways that profited them; where they served as wage labor, as in the West Country, they fought machines that threatened employment.

† The first in the series of spinning machines that laid the foundation of the factory system was that of Lewis Paul and John Wyatt (patented in Paul's name) in 1738. The key invention here was the use of rollers turning at different speeds for drawing out the fiber—a feature that became thereafter a regular component of spinning machines fitted with a flyer or equivalent. At that time, we are told, the shortage of spinning labor was nothing like what it would become in another generation; in the words of

had jumped ahead on the strength of rural manufacture (putting-out), but the dispersion of activity across hill and dale was driving up costs of distribution and collection. Meanwhile, trying to meet demand, employers raised wages, that is, they increased the price they paid for finished work. To their dismay, however, the higher income simply permitted workers more time for leisure, and the supply of work actually diminished. Merchant-manufacturers found themselves on a treadmill. In defiance of all their natural instincts, they came to wish for higher food prices. Perhaps a rise in the cost of living would compel spinners and weavers to their task.*

The workers, however, did respond to market incentives. They were contractors as well as wage laborers, and this dual status gave them opportunity for self-enrichment at the expense of the putter-out. Spinners and weavers would take materials from one merchant and then sell the finished article to a competitor, stalling now one, now another, and juggling their obligations to a fare-thee-well. They also learned to set some of the raw material aside for their own use: no backward-bending supply curve when working for their own gain. Trying to conceal the embezzlement, weavers made thinner, poorer fabrics and filled them out by artifice or additive. The manufacturer in turn tried to discourage such theft by closely examining each piece and if necessary "abating" the price of the finished article. This conflict of interests gave rise to a costly cold war between employer and employed.

The manufacturers clamored for help from the civil authorities. They called for the right to inflict corporal punishment on laggards and deadbeats (no use trying to fine them); also the right to enter the weavers' cottages without warrant and search for embezzled materials. These demands got nowhere. An Englishman's home was his castle, sacred.

Little wonder, then, that frustrated manufacturers turned their

Wadsworth and Mann, hardly serious—*The Cotton Trade,* p. 414. Yet the unevenness of the yarn produced by hand spinners—both the individual's work and from one spinner to the next—meant that weavers had to buy far more yarn than they actually used in order to have enough of a given quality. The machine promised to end that—*Ibid.*, p. 416.

* These constraints were the more vexatious in a context of rising consumer demand. The growing appetite for things should have increased the supply of labor; and so it did in the long run. But in the short, demand got ahead of supply, and manufacturers got impatient. On the link between consumption and industry, see de Vries, "Industrial Revolution."

thoughts to large workshops where spinners and weavers would have to turn up on time and work the full day under supervision. That was no small matter. Cottage industry, after all, had great advantages for the merchant-manufacturer, in particular, low cost of entry and low overhead. In this mode, it was the worker who supplied plant and equipment, and if business slowed, the putter-out could simply turn off the orders. Large shops or plants, on the other hand, called for a substantial capital investment: land and buildings to start with, plus machines.

Putting-out, moreover, was popular with everybody. The workers liked the freedom from discipline, the privilege of stopping and going as they pleased. Work rhythms reflected this independence. Weavers typically rested and played long, well into the week, then worked hard toward the end in order to make delivery and collect pay on Saturday. On Fridays they might work through the night. Saturday night was for drinking, and Sunday brought more beer and ale. Monday (Saint Monday) was equally holy, and Tuesday was needed to recover from so much holiness.

Such conflict within the industry—what a Marxist might call its internal contradictions—led logically, then, to the gathering of workers under one roof, there to labor under surveillance and supervision. But manufacturers found that they had to pay to persuade people out of cottages and into mills. *So long as the equipment in the mill was the same as in the cottage, mill production cost more.* The only operations where this law did not hold was in heat-using technologies (fulling, brewing, glassmaking, ironmaking, and the like). There the savings yielded by concentration (one hearth as against many) more than compensated for the capital costs.* Efforts to concentrate labor in textile manufacture, however, which went back in England to the sixteenth century, invariably failed. They did better in Europe, where governments tried to promote industry by subsidizing and assigning labor to large hand-powered shops—"manufactories" or "protofactories." But this was an artificial prosperity, and the withdrawal of support spelled bankruptcy.

It took power machinery to make the factory competitive. Power made it possible to drive larger and more efficient machines, thus underselling the cottage product by ever bigger margins. The hand spinners went quickly; the hand weavers more slowly, but surely. In spite

* The Chinese Communist regime learned this later when it tried to make a go of backyard blast furnaces.

of higher wages, the mills still seemed a prison to the old-timers. Where, then, did the early millowners find their labor force? Where else but among those who could not say no? In England that meant children, often conscripted (bought) from the poorhouses, and women, especially the young unmarrieds. On the Continent, the manufacturers were able to negotiate for convict labor and military personnel.

So was born what Karl Marx called "Modern Industry," fruit of a marriage between machines and power; also between power (force and energy) and power (political).

The Primacy of Observation: What You See Is What There Is

The great Danish astronomer Tycho Brahe (1546–1601) lived and worked before the invention of the telescope, but he was a keen observer and he knew all the stars he could see in the sky. And these were all there were supposed to be. One night in November 1572, however, he saw something new in the heavens, a point of light in the constellation Cassiopeia that should not have been there. This troubled him, so he asked his servants whether they saw what he saw, and they said yes, they did. For a moment he was satisfied, at least regarding his power of sight; but then he began to worry that his servants had merely wanted to reassure him and were reluctant or afraid to contradict their master, for he knew himself to be a man of pride and temper. (He had lost his nose in a duel as a youth and wore a copper—some say silver—prosthesis.) So he went out into the street and stopped some passing peasants and asked them the same question. They had nothing to gain or lose by telling the truth, and no one could be more matter-of-fact than a peasant. And they also said they saw the light. And then Tycho knew that there were more things in heaven than were dreamt of in his philosophy. He wrote up his observations in a pamphlet, *De nova stella,* published in Copenhagen in 1573, a monument in the history of science.

A note of caution: Tycho, for all his show-me empiricism, sought to find a middle way between Ptolemy and Copernicus by having the sun, circled by the planets, revolve around the earth. It takes good induction as well as good observation to do good science.

Masters of Precision

All studies of change and rates of change have to measure elapsed time. To do this, one needs a standard unit of measure and an instrument to count the units; we call that a clock. In the absence of a clock, one can substitute approximate equivalents. The seamen of the fifteenth and sixteenth centuries who wanted to count the time it took for a float to go from bow to stern by way of estimating the speed of the vessel, might use a sandglass; but if they did not have one, they could always recite Hail Mary's or some other conventional refrain; and today any practiced photographer knows that one can count seconds by reciting four-syllable expressions: one one thousand, two one thousand, three one thousand . . .

Needless to say, such idiosyncratic improvisations will hardly do for scientific purposes. For these one needed a good clock, but it took four centuries to make one. Still, scientists are ingenious people, and they found ways to enhance the precision of their pre-pendulum, pre-balance spring timepieces. One way was to use clocks with very large wheels with hundreds and even a thousand or more teeth. Tycho Brahe did this, and instead of reading the single hour hand of his clock (these early machines were not accurate enough to warrant the use of minute hands), he counted the number of teeth the wheel had turned and got much closer to the exact time elapsed. He did so to track star movements and locate these bodies on celestial maps (time was one of the two coordinates). Galileo needed even closer measurements for his studies of acceleration. Ever ingenious, he used small, hand-held water clocks rather than mechanical clocks, opening and closing the outflow hole with his finger at the start and end of the run. He then weighed the water released as a measure of time elapsed, for in those days, the balance scale was the most precise measuring instrument known.

The invention of the pendulum clock changed everything. This was the first horological device controlled by an oscillator with its own intrinsic frequency. Earlier clocks used a controller (swinging bar or circle) whose frequency varied with the force applied. After improvements (all inventions need improvements), a good pendulum clock kept time to a few seconds per day. Watches were less accurate, because they could not work with a pendulum. The invention of the balance spring, however, made it possible to get much closer to a regular rate, steady from hour to hour and day to day. A good pocketwatch, jeweled and with a decent balance, could keep time in the early eighteenth century to a minute or two a day. For the first time it paid to add a minute hand, and even a second hand.

These advances substantially enhanced the advantage that horological technology gave to Europe. What had long been an absolute monopoly of knowledge remained an effective monopoly of performance. No one else could make these instruments or do the kinds of work that depended on precision timekeeping. The most important of these, politically as well as economically: finding the longitude at sea.

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Britain and the Others

And in Europe, why Britain? Why not some other country?

On one level, the question is not hard to answer. By the early eighteenth century, Britain was well ahead—in cottage manufacture (putting-out), seedbed of growth; in recourse to fossil fuel; in the technology of those crucial branches that would make the core of the Industrial Revolution: textiles, iron, energy and power. To these should be added the efficiency of British commercial agriculture and transport.

The advantages of increasing efficiency in agriculture are obvious. For one thing, rising productivity in food production releases labor for other activities—industrial manufacture, services, and the like. For another, this burgeoning workforce needs ever more food. If this cannot be obtained at home, income and wealth must be diverted to the purpose. (To be sure, the need to import nourishment may promote the development of exports that can be exchanged for food, may encourage industry; but necessity does not assure performance. Some of the poorest countries in the world once fed themselves. Today they rely heavily on food imports that drain resources and leave them indebted, while the merest change in rainfall or impediment to trade spells disaster. At worst, they stagger from one famine to the next, each one leaving a legacy of enfeeblement, disease, and increased dependency.)